TEMPORAL RESOLUTION OF COCHLEAR OUTPUT CHANNELS IN NORMAL AND HEARING-IMPAIRED LISTENERS

by

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ABSTRACT

Temporal resolution of cochlear output channels in normal and hearing-impaired listeners was examined. Performance-intensity functions for word recognition were obtained in competing continuous and interrupted broadband noise as a function of signal-to-noise ratio (S/N). In the first experiment, normal-hearing listeners were investigated with and without a simulated high-frequency hearing loss (i.e., lowpass filtering at 2000 Hz). Word recognition improved with increasing S/N and was greater in the interrupted compared to the continuous noise. Performance was inferior with the simulated high-frequency hearing loss, relative to unfiltered listening, only in the interrupted noise condition. It was hypothesized that this performance deficit reflected a reduced ability to temporally resolve auditory information between the bursts of noise as a consequence of reduced available auditory bandwidth. The effect of sensation level (30 vs. 50 dB) on performance in the same paradigm was explored in the second study. An effect of presentation level on word recognition performance was found in only the interrupted noise. Performance was superior at 50 dB SL. These findings suggest different processes underlying word recognition under the two maskers: spectral audibility vs. temporal masking in the continuous and interrupted noise, respectively. In the third experiment performance was compared between young normal-hearing (YNH), cognitively-intact older normal-hearing (ONH), and aged-matched presbycusic listeners (OHI). The YNH group's performance was superior, followed by the ONH and OHI for both noise conditions. It was speculated that the differences in performance were a consequence of either reduced auditory bandwidth available to the older participants, inherent peripheral or central distortion in the older auditory system, nonauditory central effects and/or an interaction of these effects. A fourth experiment, revealing that normal-hearing listeners performance in continuous and interrupted noise was not worse with a simulated high frequency hearing loss (i.e., lowpass filtering at 4000 Hz) vs. without, diminished the appeal of the first suggestion. It is suggested that the dichotomization of young versus old and normal-hearing versus hearing-impaired, albeit convenient and sensible, is likely oversimplified and possibly misleading. The relationship that one may envision is a progressive deterioration of auditory threshold and suprathreshold processing with age.

LIST OF ABBREVIATIONS AND SYMBOLS USED

ANOVA:	Analysis of variance
B:	Regression coefficient (slope)
cm:	Centimeter
dB:	Decibel
df:	Degrees of freedom
dt:	Sampling interval
F:	*F* ratio
HL:	Hearing Level
Hz:	Hertz
L:	Length of track
M:	Mean
ms:	Millisecond
n:	Number in subsample
NU-6:	Northwestern University Auditory Test No. 6
OHI:	Older hearing-impaired
ONH:	Older normal-hearing
p:	Probability
P:	Power
PTA:	Pure-tone average
r:	Pearson product-moment correlation coefficient
RAU:	Rationalized arcsine unit
s:	Second
SD:	Standard deviation of the mean
SE:	Standard error of the mean
SL:	Sensation level

S/N:	Signal-to-noise ratio
SPIN	Speech Perception in Noise Test
SPL:	Sound pressure level
SRT:	Speech reception threshold
SSI	Synthetic Sentence Identification Test
s(t):	Sampling value @ time = t
VCR:	Video cassette recorder
W:	Watt
YNH:	Young normal-hearing
ω^2:	Omega squared

AUTHOR NOTES

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"Soon there will be no difference between the land and the water.
I can walk on the ice to places I've never been..."

Temporal Resolution of Cochlear Output Channels in Normal and Hearing-Impaired Listeners

Introduction

A common clinical complaint from individuals suffering with sensorineural hearing loss is an inability to understand speech in demanding listening situations of noise and/or reverberation. This handicap has been repeatedly demonstrated in experimental studies (Carhart & Tillman, 1970; Dreschler & Plomp, 1985; Festen & Plomp, 1983; Finitzo-Hieber & Tillman, 1978; Gelfand & Hochberg, 1976; Gelfand & Silverman, 1979; Moncur & Dirks, 1967; Nabelek & Mason, 1981; Nabelek & Pickett, 1974; Yacullo & Hawkins, 1987). Plomp (1978) broadly attributes the effects of cochlear pathology on speech intelligibility to attenuation (i.e., threshold elevation) and suprathreshold distortion of the speech signal (i.e., intensity, frequency, and/or temporal information subjected to distorted processing). In other words, the cause of hearing-impaired individuals' poor speech intelligibility performance in these adverse listening situations is impoverished frequency and temporal resolution, secondary to threshold elevation and loudness recruitment, in the impaired cochlea (Humes, 1982; Moore, 1985; Van Tasell, 1993).

Frequency Resolution in the Normal and Impaired Auditory System

Frequency resolution or selectivity refers to the ability of a listener to resolve/separate spectral or sinusoidal components of complex sounds (Humes, 1982; Moore, 1989). Numerous paradigms have been utilized to demonstrate the frequency resolving capacities in normal and impaired ears: masking patterns revealed with pure-tones and noiseband maskers (e.g., Fletcher, 1940; Jerger, Tillman, & Peterson, 1960; Houtgast, 1977; Nelson, 1991· Patterson, 1976; Pick, Evans, & Wilson, 1977; Rittmanic, 1962; Zwicker, 1954), loudness summation (e.g., Martin, 1974; Scharf & Hellman, 1966; Zwicker, Flottorp, & Stevens, 1957; Zwicker & Scharf, 1965), psychophysical tuning curves (e.g., Glasberg & Moore, 1986; Vogten, 1974; Wightman, McGee, & Krammer, 1977; Zwicker & Schorn, 1978), and formant masking (e.g., Danaher, Osberger, Pickett, 1973; Danaher & Pickett, 1975; Van Tasell, 1980) The phenomena observed in these studies have led researchers to describe the peripheral auditory system as containing a series of bandpass filters with continuously overlapping center frequencies. The basilar membrane of the cochlea is believed to be the basis for the auditory filters (Moore, 1986, Pickles, 1988). When attending to a signal in noise it is assumed that the listeners utilizes an auditory filter with a center frequency close to the signal The filter passes the signal and components of the noise within its bandwidth and rejects all other components of the noise background.

The "critical bandwidth" of the auditory filter, first coined by Fletcher (1940), is the range in frequency between the two upper and lower cutoff frequencies where the output of the filter has fallen 3 decibels (dB) relative to the bandpass. It is now generally accepted that the auditory filters are highly tuned and that their shape is reasonably symmetrical at moderate intensity levels (e.g., see Moore, 1989)[1]. The auditory filters have steep skirts and are rounded at the tops; however, at high intensity levels, asymmetry becomes evident as the low-frequency side becomes shallower. At frequencies below 1000 Hz the auditory filter shapes are asymmetrical with the upper skirts being steeper than the lower skirts and as, with higher frequency auditory filters, the asymmetry tends to become greater at higher intensity levels (Moore, Peters, & Glasberg, 1990). Equivalent rectangular bandwidths of auditory filters decrease with decreasing frequency With young normal listeners at moderate sound levels, for frequencies of 100, 400, 1000, 2000, 4000, and 8000 Hz, equivalent rectangular bandwidths are approximately 36, 87, 130, 240, 500, and 1175 Hz, respectively (Moore, 1989; Moore & Glasberg, 1983, Moore et al.).

It is well established that the impaired cochlea is characterized by insensitive broad auditory filters. The consequence of these broad auditory filters is a loss of audibility and reduced frequency resolution at low stimulus intensities (Bonding, 1979; Dreschler & Festen, 1986; Florentine, Buus, Scharf, & Zwicker, 1980; Glasberg & Moore, 1986; Nelson, 1991; Patterson, Nimmo-Smith, Weber, & Milroy, 1982; Stone & Moore, 1992; Tyler, Summerfield, Wood, Fernandes, 1982; Zwicker & Schorn, 1978). The perceptual consequences of an absence of normal sharp frequency tuning curves/reduced frequency resolution are threefold (Moore, 1989). First, is an augmented susceptibility to interference from noise. That is, a broadened auditory filter passes more noise components making detection of the signal more difficult. Second, is an impaired ability to separate two or more signals occurring simultaneously independent of background noise. Finally, the absence of normal sharp frequency tuning curves underlies an inability to resolve spectral peaks and valleys in auditory signals. Understandably, a positive correlation between frequency resolution as reflected on psychophysical tasks and speech recognition task performance has been documented (Arlinger & Dryselius, 1990; Dreschler & Plomp, 1980, 1985; Festen & Plomp, 1983; Preminger & Wiley, 1985; Thibodeau & Van Tasell, 1987). There are questions, however, regarding the independence of the relationship between hearing threshold level on one hand and between hearing threshold level and speech understanding on the other.

Temporal Resolution in the Normal Auditory System

Temporal resolution refers to the ability of a listener to resolve/separate auditory events or detect changes in auditory stimuli over time (Humes, 1982; Moore, 1989). Fundamentally, the perceptual processes of the detection, discrimination, and recognition of auditory events simply take time (Phillips, 1995). From the standpoint of auditory perceptual dimensions, which auditory temporal phenomena are revealed depends on the psychophysical technique employed. Two broad classes of temporal phenomena can be distinguished (Green, 1985): temporal acuity (i.e., how fast can the auditory system function) and temporal integration (i.e., the time frame over which the auditory system averages or sums acoustic information). A number of paradigms have been utilized to demonstrate the temporal resolving capacities in normal and impaired ears: detection of gaps in broadband noise, narrowband noise, and sinusoids (e.g., Buus & Florentine, 1985; Fitzgibbons & Wightman, 1982; Shailer & Moore, 1983, 1987; Plomp, 1964); discrimination of time-reversed signals (e.g., Green, 1973; Ronken, 1970); detection of amplitude changes of acoustic stimuli (e.g., Bacon & Viemeister, 1985; Viemeister, 1979); and discrimination of signals of Huffman sequences (i.e., signals that have the same long term spectra but differ in their short term spectra [Green, 1973; Patterson & Green, 1970]).

In modeling temporal resolution in the auditory system, numerous investigators have embraced the auditory filter described above. Recognition of the fact that auditory filters "ring" after the offset of signal input, led researchers to believe that temporal resolution should be constrained by auditory response time. The fact that the duration of the ringing is inversely proportional to the bandwidth of the filter suggests that high-frequency auditory filters' response times have to be the more rapid. The predicted temporal resolution, based on the response of the high-frequency auditory filters alone is, however, better than the best observed behavioral performance. This realization implied to some that there must be a process(s) higher in the auditory system that limits temporal resolution. Contemporary models of temporal resolution incorporate this concept.

Rodenburg (1977) and Viemeister (1979) each describe a four stage model of temporal resolution. In their models signal input is passed in series through a bandpass filter (i.e., the auditory filter), a nonlinear device (i.e., a half wave rectifier which passes parts of a waveform; one polarity for example), a lowpass filter, and a decision device. Moore (1989, 1993) describes a four stage model, as well; however, the second and third stages differ slightly (see Figure 1). The first two stages of these models are conceptualized as occurring in the cochlea while the latter stages occur after the auditory nerve (B.C.J. Moore, personal communication, July 13, 1995).

Moore's second stage nonlinear device has square-law properties. "The instantaneous value of the output is proportional to the square of the instantaneous value of the input. This gives a quantity which is always positive and which is related to the instantaneous power at the output of the bandpass filter" (Moore, 1989, p. 150). Others describe the nonlinearity prior to the temporal integrator as compressive in nature based on physiological evidence (e.g., Penner & Shiffrin, 1980). The third stage is a temporal integrator whose function is to sum

> the energy occurring within a certain time interval or "window". The window is assumed to slide in time, so that the output of the temporal integrator is like a running average of the input. This has the effect of smoothing rapid fluctuations while preserving slower ones. The temporal integrator is equivalent to the lowpass filter ... except that the smoothing is applied to a

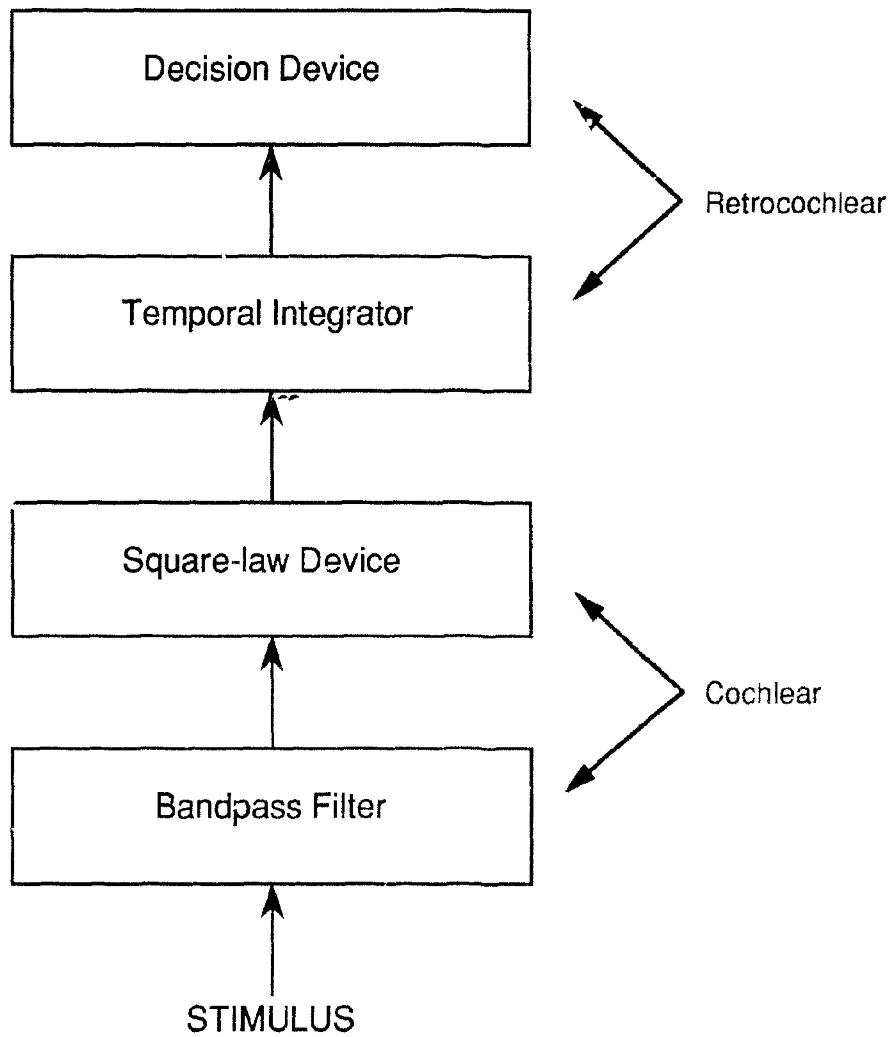

Figure 1: Block diagram of the four stage model of temporal resolution from Moore (1989). *Note.* Rodenburg (1977) and Viemeister (1979) incorporate a half-wave rectifier and a lowpass filter at the second and third stage, respectively.

power-like quantity rather than an amplitude like quantity. (Moore, 1993, p. 125)

Moore considers the temporal window to have a weighting function defined by a mathematical form (namely a rounded-exponential function). The output of the temporal integrator "becomes a weighted sum of the input power, with the recently occurring power receiving the greatest weight" (Moore, 1989, p.154). Simply put, stimulus power occurring more recently in time (i.e., close to the terminal side of the window) is more important than that occurring earlier in time (i.e., towards the leading side of the window). Moore considers the weighting function the temporal domain analog of the auditory filter in the frequency domain. Moore and colleagues (Moore, Glasberg, Plack, & Biswas, 1988; Plack & Moore, 1990) refer to the form of the weighting function as the "shape" of the temporal window. This shape, determined by examining the combined effects of forward and backward masking, is for the most part invariant with center frequency. It does, however, increase slightly with decreasing frequency. For example, the equivalent rectangular duration for center frequencies of 8100, 900, and 300 Hz is 7, 9, and 13 milliseconds (ms), respectively. The equivalent rectangular durations also increase with decreasing sound levels (e.g., 10 vs. 7 ms for 20 and 40 dB masker spectrum level at 2700 Hz). The broader the temporal window, the longer the temporal integration or poorer the resolution. The window's shape is asymmetrical with the times before the center having shallower slopes than times after it, reflecting the characteristic above that stimulus occurring more recently in time is more important than that occurring earlier.

The nature or rules governing the decision device are somewhat nebulous. Moore (1989) suggests that the rules employed by the device may depend on the nature of the psychophysical task. For example, it may work with a detection function looking for a stimulus to exceed a certain magnitude or with a discrimination function comparing different outputs from the lowpass filter/temporal integrator. Although the generation of "decision rules" is possible it is, unfortunately, difficult if not impossible to demonstrate that they are actually being engaged (Moore).

In summary, models of temporal resolution proposed by Moore (1989, 1993), Rodenburg (1977), and Viemeister (1979) are similar: Stimuli pass through four stages from the periphery to a central decision mechanism whereby some smoothing of the stimuli occurs such that rapid fluctuations are lost while slower ones are sustained. Moore (1993) states that the smoothing process almost certainly operates on neural activity, however, "the most widely used models are based on smoothing a simple transformation of the stimulus, rather than its neural representation. This is done for simplicity and mathematical convenience" (p. 124) One limitation to the models is that they only account for tasks that necessitate within-channel resolution (i.e., within one particular frequency channel). There are tasks that have been shown to require across-channel comparisons (i.e., across different frequency channels) Discrimination of Huffman sequences (Green, 1973; Patterson & Green, 1970) and detection of offset asynchrony in multicomponent complexes (Zera & Green, 1993) are examples of such tasks. Finally, if one considers a four stage model it is apparent that temporal resolution may be constrained by four factors "the shape and bandwidth of the initial filter, the type of nonlinearity assumed; the cutoff frequency and slope of the lowpass filter (or the shape of the weighting function describing the temporal window); and the nature and sensitivity of the decision device" (Moore, 1989, p.154). As the first two stages of these models are conceptualized as occurring in cochlea while the latter stages in the central auditory system, it stands to reason, as well, that temporal resolution deficits may either be peripheral or central in nature.

Temporal Resolution in the Impaired Cochlea

Let us return to the issue of broad auditory filters in the impaired cochlea. Although they are detrimental for frequency resolution, it would seem intuitive that they would be beneficial for temporal resolution (Buus & Florentine, 1985; Moore, 1985). As noted above, auditory filters ring after the offset of input and the duration of the ringing is inversely proportional to the bandwidth of the filter. As wider auditory filters exhibit faster decay they should, as well, exhibit better temporal resolution than narrower filters, due to the absence of auditory activity. In other words, "since listeners with cochlear impairments typically have broader-than-normal auditory filters, the temporal response of their filters should be correspondingly more rapid than normal, and this should lead to improved temporal resolution" (Moore, 1985, p.199).

In practice, however, temporal resolution often appears to be poorer in listeners with sensorineural hearing losses than in normals. For example, gap detection thresholds have repeatedly been reported to be elevated among hearing-impaired listeners (Buus & Florentine, 1985; Fitzgibbons & Wightman, 1982; Florentine & Buus, 1984; Glasberg, Moore, & Bacon, 1987; Irwin, Hinchcliffe, & Kemp, 1981; Moore & Glasberg, 1988; Trinder, 1979; Tyler et al., 1982). In addition, hearing-impaired listeners have shown detriments in performance relative to normal listeners on other measures of temporal resolution: temporal integration (Gengel & Watson, 1971), forward and backward masking (Cudahy, 1977; Cudahy & Elliot, 1975, 1976; Danaher, Wilson, & Pickett, 1978; Kidd, Mason, & Feth, 1984; Zwicker & Schorn, 1982), detection of tone bursts in modulated noise (Humes, 1990), and temporal modulated transfer functions (Bacon & Viemeister, 1985).

There are reports, however, that suggest that the temporal resolving capacities of hearing-impaired individuals may not be inferior to normal listeners. On closer examination, it appears that findings reflecting performance of cochlear hearing-impaired listeners on temporal resolution tasks are equivocal. Differences among studies may be attributed to varying task demands that either exploit impaired (typically high-frequency) cochlear channel deficits or equate performance with tasks designed for normal functioning (typically low-frequency) cochlear channels.

Three important factors have been identified as contributing to hearing-impaired listeners' less than favorable performance on temporal resolution tasks (Moore, 1993). The first is the degree to which stimuli in the temporal resolution tasks fluctuate in amplitude. As noted above, gap detection thresholds in hearing-impaired listeners have been reported to be elevated. When gap detection is determined for sinusoids as opposed to bands of noise, however, small if any differences are found between the hearing-impaired and normal listeners (Moore & Glasberg, 1988; Moore et al., 1989). Moore and colleagues (Glasberg et al., 1987; Moore & Glasberg) suggest that the impaired performance in noise may be a consequence of loudness recruitment. That is, the instantaneous fluctuations of the narrow bands noise may be perceived as louder than normal in the impaired cochlea making the gap detection task more difficult, as dips in the noise might be confused with the gap to be detected. To buttress this posit. Glasberg and Moore (1992) demonstrated that normal listeners, when faced with magnified envelope fluctuations in narrowband noise, akin to loudness recruitment suffered by hearing-impaired listeners, display inferior gap detection performance.

A second factor influencing temporal resolution performance relates to the reference intensity level of the stimulus presentation. Often when normal-hearing listeners are compared with hearing-impaired listeners at equal sound pressure levels (SPLs), the former exhibit superior performance on temporal resolution tasks. When the same two groups are evaluated at equal sensation levels (SLs), performance differences are negated (Fitzgibbons & Wightman, 1982; Glasberg et al., 1987; Moore & Glasberg, 1988; Moore et al., 1989; Tyler et al., 1982). It is also well know that normal listeners performance on temporal resolution tasks decreases at lower SLs (Bacon & Viemeister, 1985; Fitzgibbons, 1983; Plomp, 1964; Shailer & Moore, 1985; Viemeister, 1979). Unfortunately, performance between normal-hearing and hearing-impaired listeners can not often be evaluated at equivalent SLs because of loudness recruitment experienced by hearing-impaired listeners.

A third factor limiting temporal resolution performance in hearing-impaired listeners is the listening bandwidth available to the hearing-impaired. There are two means of embracing this concept. The first is in the spectral domain. If the signal, or part thereof, is inaudible it seems likely that task performance would suffer for this reason alone. The modulation thresholds for sinusoidally amplitude-modulated broadband noise findings of Bacon and Viemeister (1985) are a case in point. Sensitivity to amplitude modulation and the highest detectable modulation frequency was poorer in hearing-impaired listeners. These effects were level dependent, as well. That is, as the carrier spectrum level decreased so did sensitivity and the highest detectable modulation frequency. This pattern was attributed to the fact that the higher frequencies were inaudible to the hearing-impaired listeners (i.e., as Bacon and Viemeister suggest, a narrower effective internal bandwidth). Normal-hearing participants, with a simulated high-frequency hearing loss, exhibited a pattern of performance similar to that of the hearing-impaired listeners. In a follow-up study Bacon & Gleitman (1992) evaluated modulation detection thresholds in hearing-impaired listeners who had relatively flat mild-to-moderate losses. At comparable SLs temporal modulation transfer functions for seven of eight hearing-impaired participants were similar to normal controls. The findings from both studies suggest that temporal resolution task performance may be dependent on audibility. Turner, Souza, and Forget (1995) have demonstrated that when audibility is compensated for, temporal acuity of listeners in terms of speech recognition is not impaired. They investigated the ability to use temporal cues in speech directly with 16 hearing-impaired listeners. Processed (i.e., where the spectral information was removed resulting in a time-varying speech envelope amplitude-modulated noise carrier) and unprocessed nonsense syllables were presented to participants. Recognition of the envelope signals in quiet and noise was examined. There was no difference in performance between the hearing-impaired listeners and normal controls suggesting that hearing-impaired listeners, when compensated for the loss of audibility, do not exhibit temporal acuity deficits in terms of speech recognition compared to normal-hearing listeners.

The second way of conceptualizing listening bandwidth as limiting temporal resolution in the hearing-impaired listener is in the temporal domain. Hearing-impaired listeners are at a disadvantage due to the functional loss of the high-frequency region of the cochlea. Since it is the population of high-frequency cochlear output channels that have the best temporal resolution, it has been suggested that the loss of these channels is somewhat responsible for poor temporal resolution performance (Bacon & Viemeister, 1985; Buus & Florentine, 1985; Moore, Glasberg, Donaldson, McPherson, & Plack, 1989; Shailer & Moore, 1987). That is, functional hearing in the cochlearly impaired (i.e., those who typically demonstrate high-frequency losses) is confined to low-frequency channels whose (normal) temporal resolution is inherently inferior to that of the high-frequency channels. Consequently, their performance on temporal resolution tasks appears impaired relative to normal listeners. This speculation has been given credence by a number of studies that have found that the performance of normal listeners with simulated high-frequency hearing losses mimics hearing-impaired listeners performance on various temporal resolution tasks: forward and backward masking in "masking period patterns" (Zwicker & Schorn, 1982), gap detection (Buus & Florentine, 1985), temporal modulated transfer functions (Bacon & Viemeister, 1985), and detection of tone bursts in modulated noise (Arlinger & Dryselius, 1990). Further, there is evidence from animal literature that the temporal coding properties of the cochlea are not impaired following outer hair cell degeneration (Harrison & Evans, 1979).

The Relationship Between Temporal Resolution and Speech Understanding

Previously it was implied that impoverished temporal resolution was in part responsible for hearing-impaired individuals' poor speech understanding performance in adverse listening situations. It seems intuitive to suggest that one should find a relationship between speech intelligibility performance and temporal resolution as reflected on psychophysical tasks. A number of researchers have examined this possibility. Tyler et al. (1982) investigated four measures of temporal resolution (i.e., temporal integration, gap detection, temporal difference limen, and gap difference limen) among 16 hearing-impaired participants. Additionally, measures of identification and discrimination of synthetic syllables differing in voice onset time and word recognition in noise were obtained. The authors reported "increased temporal difference limen and longer gap-detection thresholds were found to correlate significantly with reduced speech intelligibility in noise, even when the effects of pure-tone thresholds were partialied out" (Tyler et al., p.740).

Dreschler and Plomp (1985) similarly employed a test battery approach to investigate the relationship between psychophysical task performance and speech perception. Forward and backward masking and gap detection thresholds at 500, 1000, and 2000 Hz were investigated as indices of temporal resolution along with phonemic perception and speech perception tests. Forward and backward masking and gap detection were all statistically related to speech perception in noise. The authors concluded that the findings support the notion of the negative effect of deficient temporal resolution on speech perception.

Irwin and McAuley (1987) conducted three experiments to investigate the relationship between temporal acuity (i.e., gap detection threshold) and speech perception in noise and reverberation in hearing-impaired listeners. Pearson product moment correlations revealed a moderate relationship between gap detection threshold and speech perception. A principal components analysis yielded a pattern consistent "with the interpretation that poor temporal acuity, as summarized by a time constant, is accompanied by degraded perception of speech distorted by noise and reverberation" (Irwin & McAuley, p.1564).

Arlinger and Dryselius (1990) also reported a significant correlation between temporal resolution (assessed with a forward masking paradigm) and word recognition in noise between 10 normal-hearing and 11 participants with moderate, high-frequency, sloping hearing losses. Although, the single audiometric index with the highest correlation with speech recognition in noise was the average hearing threshold levels at 2000 and 4000 Hz, it was followed by a correlation with indices of forward masking (cf. 0.7 and 0.6).

The findings of Festen and Plomp (1983) are to the contrary of those cited above. Twenty-two hearing-impaired listeners were subjected to a battery of tests including sentence recognition in quiet and noise, frequency resolution, and temporal resolution tasks (i.e., intensity modulated noise and forward and backward masking). A principal components analysis revealed two distinct clusters, one for frequency resolution and one for audiometric loss, explaining 48.1% and 17.6% of the variance, respectively. The correlation between clusters was weak. There were no statistically significant correlations between any temporal resolution indices and sentence recognition performance.

Similarly, Dubno and Dirks (1990) failed to find a relationship between temporal resolution and speech understanding. Nine normal-hearing and 24 hearing-impaired listeners were assessed with a forward masking task and recognition of synthetic consonant-vowel syllables. The authors found no apparent relationship between consonant recognition and a time constant of recovery trom forward masking. The findings of the study need to be cautiously interpreted as only one index of temporal resolution was employed.

The Interrupted Noise Paradigm

Word recognition is routinely used as a measure of auditory function. Open set word recognition testing in quiet has been criticized on a number of grounds including a lack of face validity, an inability to differentiate normal and sensorineural impaired listeners, and an inability to differentiate the performance of hearing aids (e.g., Bess, 1983; Danhauer, Doyle, & Lucks, 1985; Surr & Schwartz, 1980). Assessment of word recognition ability in competing background noise has been advocated as a means of increasing face validity (Bess, Olsen, & Matkin, 1991) and improving test sensitivity (e.g., Cohen & Keith, 1976; Cooper & Cutts, 1971; Findlay, 1976). The most common type of background competing stimulus is continuous broadband noise due to its availability on clinical audiometers (Bess).

One may acknowledge that continuous noise as a competing signal is not typically what is encountered in everyday listening situations. This notion, that noise may be intermittent and fluctuate in loudness, was recognized in seminal studies investigating speech intelligibility Miller (1947) noted that the effectiveness of a masking sound on speech was dependent upon its level relative to the speech signal, acoustic spectrum, and temporal continuity. He was the first to report on the effectiveness of an "interrupted" masker. Percent word articulation scores were investigated as a function of the percentage of time that a white noise masker was on. It was found that masking effectiveness decreased with a reduction in the duty cycle of the masker For a signal-to-noise ratio (S/N) of -6 dB, compare percent articulation scores of approximately 5%, 60%, 75%, 90%, and 100% for noise-on-times of 100%, 80%, 65%, 50%, and 25%, respectively

Miller and Licklider (1950) examined the effect of the frequency of interruption of the masking noise on percent correct word articulation When the noise masking interruption increased from 1 to 10 Hz speech intelligibility improved. As the frequency of interruption increased above 10 Hz, however, intelligibility decreased. At an interruption rate of several hundred times per second (s) the noise essentially assumed a continuous characteristic The authors also reported that the effect of regular versus random interruptions were qualitatively similar. Similar results have been reported by several other investigators (Carhart, Tillman, & Johnson, 1966; Pollack 1954, 1955; Wilson & Carhart, 1969). Pollack (1955) additionally reported that if the silent periods between successive noise bursts were filled with noise, masking efficiency improved. When the "inter-burst ratios" (i e , the difference in dB between two successive noise bursts and the level of noise filling the otherwise silent interval between them) increased to -6 dB from -18 dB and -12 dB, percent words correct fell from approximately 65% and 40% to 25 %, respectively. There was little difference between the -18 dB inter-burst ratio and a "silent" inter-burst ratio.

The effect of interrupted masking on speech stimuli other than monosyllabic words has also been reported. Speech reception thresholds have been reported to be lower for spondees (i.e., disyllabic words pronounced with equal stress on both syllables) presented in white noise interrupted at rates of either 1, 10, or 100 Hz with a duty cycle of 50% (Wilson & Carhart, 1969) and for sentences presented in a speech spectrum noise interrupted at a rate of 10 Hz with a duty cycle of 50% (de Laat & Plomp, 1983) compared to continuous noise. Wilson and Punch (1971) performed two experiments to evaluate the effect of duty cycle and level of an interrupted masker on spondee thresholds among 15 normal-hearing participants. Spondee thresholds increased with increasing duty cycles and masker levels. There was also an interaction between duty cycle and masker level. At higher masking levels there were greater increases in masking efficiency with increasing duty cycles. Calearo, Teatini, and Pestalozza (1962) reported that intelligibility of sentences decreases with increasing interruption rate (i.e., from 20 to 500 interruptions/s).

In a comprehensive study Dirks, Wilson, & Bower (1969) studied intelligibility functions for spondaic and monosyllabic words and identification functions for synthetic sentences in interrupted noise with rates of 1, 10, and 100 Hz with a duty cycle of 50%. As with previous experiments, masking effectiveness was reduced in the interrupted conditions for all speech materials. There were, however, different patterns of interference for the various speech stimuli. The greatest release from masking (i.e., the decrease in masking efficiency relative to the continuous noise masking condition) for the spondaic and sentence materials occurred at the 1 interruption/s condition and decreased with increasing interruption rates. For the monosyllabic material the greatest release from masking occurred at 10 interruptions/s at favorable S/Ns. As the S/Ns deteriorated the slope of the function resembled that found with continuous noise. At the poorest S/Ns the slope flattened and proceeded to drop gradually. These findings with monosyllabic materials were replicated by Dirks and Bower (1970). The discrepancies, between studies cited above, in masking effectiveness with interruption rate and speech materials have been attributed to differences in the intrinsic redundancy of spondee and sentence stimuli (Dirks & Bower, 1971). Finally, similar performance-intensity functions have been reported for intervocalic-vowel syllables in interrupted noise compared to monosyllabic words (Howard-Jones & Rosen, 1993).

It is of interest to note that a similar release from masking has been observed in other time-varying maskers of the same overall level. Better speech intelligibility is observed with periodically amplitude-modulated competing white noise compared to continuous noise (Carhart et al., 1966; Carhart, Tillman, & Greetis, 1968; Eisenberg, Dirks, & Bell, 1995; Shapiro, Melnick, & VerMeulen, 1972). Generally, performance increases with modulation depth and decreasing modulation rate (to a rate of about 20/s). Sentence reception thresholds are lower in amplitude-modulated compared to continuous noise (Festen, 1987; Festen & Plomp, 1990). Interfering speech from a second voice, as well, commands less masking efficiency than a continuous broadband masker (Carhart et al., 1966; Duquesnoy, 1983a; Festen; Festen & Plomp).

Speech Perception in Interrupted Noise: A Temporal Resolution Phenomenon?

In assessing speech intelligibility performance in interrupted noise, Miller (1947) commented that "apparently the recovery of the ear is rapid enough, and our ability to integrate fragments of speech is great enough, that any periodic interruption of masking sounds lowers its masking effectiveness" (p. 122).

Others have suggested that listeners get "glimpses" (Miller & Licklider, 1950) or "looks" (Dirks et al., 1969) of each word between the gaps of noise and are able to patch the information together in order to identify the specific word. Pollack (1955) proposed that there was some "recovery" in the auditory system between the intervals of noise. The prevailing thought from these studies was that rapid interruptions of short durations had little influence on masking effectiveness and as such, noise stimuli with those characteristics performed as if continuous. Rapid interruptions are effectively eliminated due to the temporal resolution limitations of the auditory system. Only when the interruptions are slowed can the auditory system take advantage and a release from masking over effective continuous masking can occur.

Dirks and colleagues (Dirks et al., 1969; Dirks & Bower, 1970) were the first to suggest and investigate that two phenomena were responsible for the masking effect on speech intelligibility observed in interrupted noise with monosyllabic stimuli. One was due to the simultaneous masking during the noise burst while the other was temporal masking during the inter-burst interval. Temporal masking refers to a situation where the signal and the masker are not simultaneous in time. Forward masking occurs when the masker precedes the signal and elevates its detection threshold while backward masking occurs when a signal precedes a masker and has an elevated threshold (Elliot, 1962a, 1962b, 1971; Fastl, 1976, 1977, 1979; Osman & Raab, 1963; Penner, 1974; Weber & Moore, 1981). Dirks and colleagues believed that the silent intervals were not "free" from the influence of noise bounding them. In other words, the silent gaps were subject to "spill-over" from the noise as a consequence of forward and backward masking. It had been known previously, and replicated subsequently, that nonspeech signals positioned in the silent gap in otherwise continuous noise are influenced by both forward and backward masking and exceeds what would be expected by a simple summation of the two (Elliot, 1969; Fastl, 1976, 1977, 1979; Patterson, 1971; Pollack, 1964; Robinson & Pollack, 1973; Wilson & Carhart, 1971). In an ingenious study Dirks and Bower set out to investigate the effect of forward and backward masking of speech intelligibility in interrupted noise with monosyllabic stimuli.

Three experimental conditions were employed by Dirks and Bower (1970) to investigate intelligibility functions for monosyllabic words: speech interrupted by silent intervals at rates of 1, 10, and 100/s; speech alternated with noise at rates of 1, 10, and 100/s; and speech in interrupted noise (0.5 noise-time fraction) at rates of 1, 10, and 100/s. The noise was held constant at 80 dB SPL while the speech signal varied. Comparison of the first two conditions provided a measure of the effect of forward and backward masking during the noise free interval. Comparison of the second and third conditions yielded an estimate of how much the speech during the noise interval contributes to intelligibility. The results suggested that as the rate of interruptions increase from 10/s to 100/s the effects of forward and backward masking increase. In other words, as the window between the noise bursts decreases the masking effects become more pronounced. At a slow interruption rate little masking is observed except at very unfavorable S/Ns. Further, speech heard during the noise burst adds to the intelligibility at favorable S/Ns for the slow 1/s interruption rate. Finally, speech heard during the noise bursts at 100/s interruptions had minimal effect on intelligibility and at 10/s "the function was formed entirely by the speech heard during the noise free interval" (Dirks & Bower, p. 1008).

As to the question of whether speech perception in interrupted noise is a temporal resolution phenomenon, the answer has to be yes. Adequate temporal resolution is required as the listener must sustain the temporal gaps in the masker thereby taking advantage of the favorable S/Ns. The release from masking in interrupted noise is therefore limited by the auditory system's ability to resolve acoustic information in the silent gaps between the successive noise bursts. The data from Dirks and Bower (1970) suggest that for young normal-hearing listeners the minimal gap whereby speech can be resolved appears to be approximately 5 ms as the noise masker interrupted 100/s was almost as efficient as a continuous masker.

Employing the Interrupted Noise Paradigm to Reveal Temporal Resolution Deficits

D.P. Phillips, Rappaport, and Gulliver (1994) pursued the notion that hearing-impaired listeners' temporal resolving power is limited by their low-frequency channel capacities with a word recognition-in-noise paradigm. Specifically, word recognition performance was investigated in continuous broadband and interrupted noise in normal and noise-induced hearing-impaired listeners as a function of S/N. The interrupted noise was shaped to simulate the temporal envelope of speech. It was speculated that the paradigm challenged listeners' temporal processing mechanisms as listening in interrupted noise requires resolving speech information in the gaps of silence. Fifteen listeners with specifically noise-induced high-frequency losses and 15 normal-hearing listeners served as participants. It was demonstrated that the hearing-impaired participants' performance, as reflected by performance-intensity functions, was not significantly different from normals in the continuous broadband noise condition but was significantly impaired in the interrupted noise condition. It was hypothesized that the difference in performance in the interrupted noise condition was related to hearing-impaired listeners' restriction to low-frequency channels and, as such, a reduced ability to temporally resolve auditory information between the gaps of noise. D.P. Phillips et al. reasoned:

> Because the spectra of the two noise maskers were virtually identical, the selectivity of the defect must be associated with the temporal differences between the maskers. This selectivity of the impoverished performance confirmed ... that the patients with cochlear hearing loss had a poorer ability to recognize the speech fragments that occurred in the silent periods of the masker and, therefore, that they evidenced some form of temporal processing deficit. (p. 683)

In the first proposed experiment of this dissertation, it was therefore hypothesized that if hearing-impaired listeners' detriment in performance was a consequence of restricted low-frequency channel capacity with inherently inferior temporal resolution, normal-hearing listeners should exhibit a similar detriment in performance on the same task if studied under conditions that simulate a hearing loss. That is, one would predict that normal-hearing listeners, with a simulated high-frequency hearing loss, would display an impaired performance in interrupted noise akin to noise-induced hearing-impaired listeners due to the normal, but inherently poorer, low-frequency channel ability to temporally resolve auditory information occurring in the gaps of the interrupted noise. If similarities are in fact evident, then one may conclude that performance is attributable to hearing-impaired listeners' and normal listeners' restricted low-frequency channel capacities. If differences are evident between the real and simulated impairments, then one must conclude that abnormal temporal processing is a consequence of activity through the impaired high-frequency cochlear channels. The purpose of the first experiment was to investigate this speculation by comparing normal-hearing listeners' performance in continuous and interrupted broadband noise as a function of S/N with and without a simulated high-frequency hearing loss.

Presbycusis

In the simplest terms, presbycusis is a decline in hearing ability with aging. In general, an individual suffering from presbycusis presents with a bilateral, predominantly high-frequency, hearing loss with an accompanying difficulty in understanding speech in adverse listening conditions that would not be explained by the loss of hearing sensitivity alone (Bergman, 1980; Marshall, 1981; Willott, 1991; Working Group on Speech Understanding and Aging, 1988). Although this concept of declining auditory ability has general appeal there remains some discussion as to how one defines presbycusis and uses the term to classify older individuals with hearing impairment (e.g., Gelfand & Silman, 1985; Marshall; Lowell & Paparella, 1977; Paparella, 1978). One concern is the confounding of changes in hearing associated with aging and concomitant changes from other influences. Kryter (1983) delineates the effects of presbycusis, sociocusis, and nosocusis. They respectively refer to changes in hearing sensitivity associated with aging, exposure to environmental sounds associated with every day living, and pathological insult. Willott notes that presbycusis has traditionally referred to elevation of audiometric thresholds, but argues that one should not divorce the fact that audition entails more than simply detection; it encompasses multiple levels of processing whose end product is perception (or lack thereof). With this in mind, his definition has intuitive appeal and is hence adopted:

> Presbycusis refers to the decline of hearing associated with various types of auditory system dysfunction (peripheral and/or central) that accompany aging and cannot be accounted for by extraordinary ototraumatic, genetic, or pathological conditions. The term "presbycusis" implies deficits not only in absolute thresholds but in auditory perception, as well. (pp. 2-3)

The demographics of aging and hearing loss are staggering. Hearing loss is the third highest chronic health complaint among the elderly (National Center for Health Sciences, 1987). Prevalence studies suggest that anywhere from 20% to 83% of individuals 55 years and older suffer hearing impairment (e.g., Davis, 1989; Gates, Cooper, Kannel, & Miller, 1990; Kryter, 1983; Leske, 1981; Moscicki, Elkins, Baum, & McNamara, 1985; Pearson, Morrell, Gordon-Salant, Brant, Metter, Klein, & Fozard, 1995; Plomp, 1978). Discrepancies among prevalence estimates are attributed to the criteria adopted for defining hearing impairment, test protocol, population characteristics, and test environment. General trends, however, point to hearing impairment increasing dramatically with successive decades among individuals over 55 years of age. Approximately 25% to 40% of individuals over 65 years of age compared to approximately 90% over 80 years of age display hearing loss (Bess, Lichtenstein, & Logan, 1991). Considering estimations of individuals in their middle and later years in North America, some 8 to 12 million elderly people are considered to be hearing-impaired (Bess et al.).

Histopathologic and Morphologic Findings Relevant to Presbycusis

Histopathologic and morphologic findings from studies of human temporal bones and brains have revealed age-related structural changes at all levels of the auditory system. Degenerative changes and morphological changes in the cochlea include loss of hair cells particularly at the basal end and atrophy of supporting cells (e.g., Engstrom, Hillerdal, & Laurell, 1987; Johnson & Hawkins, 1972a, 1972b: Schuknecht, 1964; Zallone, Teti, Balle, & Iurato, 1987). Age-related changes have been observed in the ganglion cells/auditory nerve fibers (e.g., Engstrom et al.; Johnson & Hawkins, 1972a; Krmpotic-Nemanic, 1971; Nadol, 1979; Schuknecht; Spoendlin & Schrott, 1989,

1990) and stria vascularis (e.g., Engstrom et al.: Johnson & Hawkins, 1972b; Krmpotic-Nemanic; Schuknecht; Suga & Lindsay, 1976; Takahashi, 1971).

Numerous central auditory pathway anomalies attributed to aging have also been observed including changes in the ventral cochlear nucleus (Arnesen, 1982; Hansen & Reske-Neilson, 1965; Kirikae, Sato, & Shatara, 1964; Konigsmark & Murphy, 1972), trapezoid body (Casey & Feldman, 1982, 1985a, 1985b), lateral lemniscus (Ferraro & Minckler, 1977a), inferior colliculus (Ferraro & Minckler, 1977b; Kirikae et al ; Hansen & Reske-Neilson), medial geniculate body (Kirikae et al.), and cerebral cortex (Brody, 1955; Hansen & Reske-Neilson; Scheibel, Lindsay, Tomiyasu, & Scheibel, 1975). These central auditory pathway anomalies include (although not necessarily uniform across all structures and individuals) loss of cells, decreased cell nuclei volume, change in cell shape, decreased dendritic branching, vascular alterations, and an accumulation of lipofuscin within neurons. Similar age-related neuropathology has been documented in other nonauditory central structures (for a review see Duara, London, & Rapoport, 1985). There is some suggestion that age-related changes in the central nervous system may mediate a general "slowing" or decline in the speed of behavior (for a review see Birren, Woods, & Williams, 1980). Although there is a plethora of evidence demonstrating histopathologic and morphologic changes in aged human specimens, one must show some restraint in interpretation of the data as it is not known if the changes are associated with aging or due to post-mortem change or terminal disease (Duara et al.; Willott, 1991; Working Group on Speech Understanding and Aging, 1988). Further, although structural age-related degenerative changes observed at all levels of the auditory system would intuitively suggest many functional consequences, none have been established.

Willott (1991) identifies three factors that have been troublesome with the interpretation of research findings investigating age-related histopathologic and morphologic findings in aging humans: it is difficult to obtain post-mortem samples that are free from autolytic artifact; "central" changes may be a consequence of peripheral sensorineural pathology; and environmental and genetic factors may interact with general aging effects. The use of animal models have been advocated as a means to alleviate these problems. For the most part studies of aging in animals have independently confirmed evidence for both peripheral and central alterations found with hum ns and have offered additional evidence: age-related changes vary with cell type; within- and between-individual variability in neuropathology is observed: genetic factors may influence histopathology; and connections between central auditory components persist despite insult from biological aging and peripheral pathology (Willott). In spite of accumulating evidence from animal models a caveat remains:

> As was the case with histopathological observations on humans, the functional significance of age-related change in animals is difficult to assess. While we can describe the histopathological changes in animals in great detail, it is more difficult to relate them to complex perceptual capacities. Behavioral studies are sorely needed to determine how far the histological changes can advance before perceptual abilities are affected. (Willott, p.121)

Auditory Function in the Presbycusic Listener

The first and most documented evidence of auditory dysfunction in the presbycusic listener is a loss of hearing sensitivity as reflected in elevated pure-tone thresholds. The typical audiometric configuration is hearing thresholds within a normal range to 1000 Hz (i.e., ≤ 25 dB HL) with a bilateral mild sloping to moderately-severe sensorineural loss (i.e., thresholds ≥ 25 dB HL to approximately 60 to 70 dB HL [e.g., Brant & Fozard, 1990; Corso, 1963; Erlandsson, Hakanson, Ivarsson, & Nilsson, 1982; Gates et al., 1990; Kryter, 1983, Moscicki et al., 1985; Pearson et al., 1995; Plomp, 1978; Robinson & Sutton, 1979]). There are some cases of presbycusis that have been documented, however, not to follow a high-frequency sloping configuration but rather have a flat configuration (Dayal, Kane, & Mendelsohn, 1970). Generally hearing loss begins as early as the forth decade of life and increases dramatically with age, particularly after the sixth decade. Loss of hearing sensitivity is greater in males at most ages although males tend to have better low-frequency hearing sensitivity than females (Jerger, Chmiel, Stach, & Spretnjak, 1993; Pearson et al.). There is some disagreement as to whether there are in fact differences between males and females when sociocusis differences are controlled for (cf. Kryter and Pearson et al.).

Age-related changes have been discovered in auditory function as evaluated with other nonspeech and speech materials. Binaural processing, as assessed behaviorally with masking level differences (Grose, Poth, & Peters, 1994; Tillman, Carhart, & Nicholls, 1973) and a dichotic digits task (Martin & Cranford, 1991) or electrophysiologically with late auditory evoked potentials (Cranford & Martin, 1991), has also been shown to deteriorate with age. Frequency selectivity (as assessed by psychophysical tuning curves or derived auditory filter shapes) has been found to be poorer in elderly listeners (Glasberg, Moore, Patterson, & Nimmo-Smith, 1984; Lutman, 1991; Lutman, Gatehouse, & Worthington, 1991; Patterson et al., 1982; Zwicker, & Schorn, 1978). On the other hand upward spread of masking was not found to differ between young and elderly hearing-impaired listeners (Klein, Mills, & Adkins, 1990).

Findings of speech understanding performance in elderly presbycusic listeners in quiet on first glance seem to be equivocal. There have been reports that their performance is equivalent to younger listeners (e.g., Dubno, Dirks, & Morgan, 1984; Findlay & Denenberg, 1977; Gang, 1976; Gordon-Salant, 1987; Harris & Reitz, 1985; Holmes, Kricos, & Kessler, 1988; Kasden, 1970; Rintelmann, Schumaier, Jetty, Burchfield, Beasley, Mosher, Mosher, & Penley, 1975; Schum, Mathews, & Lee, 1991; Townsend & Bess, 1980) while others suggest otherwise (e.g., Duquesnoy, 1983a, 1983b; Gelfand, Piper, & Silman, 1986; Helfer, & Wilber, 1990; Humes, Nelson, & Pisoni, 1991; Humes & Roberts, 1990; Plomp & Mimpen, 1979). On closer examination the differences may be attributed to the fact that elderly listeners failed to achieve maximum performance due to low presentation levels and/or because older listeners with substantial hearing losses were included in the samples (Gang; Gordon-Salant; Kasden; Marshall, 1981; Willott, 1991).

There is overwhelming evidence that presbycusic listeners are significantly impaired in nonoptimal listening conditions. Performance detriments in speech understanding have been demonstrated in broadband noise (Dubno et al., 1984; Gelfand et al., 1986; Gimsing, 1990; Gordon-Salant, 1987; Hargus & Gordon-Salant, 1995; Humes et al., 1991; Jokinen, 1973; Plath, 1991, Plomp & Mimpen, 1979; Prosser, Turrini, & Arslan, 1991; Schum et al., 1991; Souza, & Turner, 1994; von Wedel, von Wedel, & Streppel, 1991a), babble (Dubno et al., 1984; Findlay & Denenberg, 1977; Gelfand et al., 1986), competing speech (Bergman, 1980; Carhart & Tillman, 1970; Duquesnoy, 1983a), and reverberation (Duquesnoy & Plomp, 1980; Harris & Reitz, 1985; Helfer, 1992; Helfer, & Wilber, 1990; Nabelek & Robinson, 1982). The results of these findings, although convincing, are not necessarily easy to interpret. The contributing factors responsible for this detriment in performance in less than optimal listening conditions are hard to isolate. Three potential contributing factors have been identified: peripheral hearing loss, central auditory system dysfunction, and/or cognitive deficits (Marshall, 1981; Willott, 1991; Working Group on Speech Understanding and Aging, 1988). That is, loss of hearing sensitivity, loudness recruitment, impaired frequency and temporal resolution associated with peripheral hearing loss; impaired or slowed central auditory processing; and/or a general slowing or reduction of cognitive-linguistic processing in any sensory channel associated with advanced aging may be responsible for impaired speech understanding in the presbycusic listener The interaction of all three factors has been theoretically proposed (Willott) Numerous researchers have attempted to quantify the contributions peripheral hearing, central auditory system, and/or cognitive deficits on speech understanding in less than optimal listening conditions

Speech Understanding Difficulties in Presbycusis: Source of the Deficit

Several groups of researchers have suggested that the decline in speech understanding among presbycusic listeners can be accounted by the peripheral hearing loss alone. For example, Grady, Grimes, Pikus, Schwartz, Rapoport, & Cutler (1984) examined the relationship between aging and auditory function among 36 healthy males ranging in age from 21 to 83 years. Auditory function was assessed with a battery of tests pure-tone thresholds, speech reception thresholds, word recognition, lowpass filtered speech, and binaural fusion. Correlational coefficients were computed with hearing loss being partialled out. It was found that "some measures of auditory processing of speech stimuli do not show a significant relation to age when effects of peripheral hearing loss are taken into account" (Grady et al., p. 107) Humes and Roberts (1990) employed three groups of 12 listeners to evaluate the contribution of audibility on speech recognition in the elderly: young normal-hearing adults, elderly hearing-impaired, and young normal-hearing adults with a simulated hearing loss. Performance was assessed with the Nonsense Syllable Test in quiet, noise, and reverberation. As expected, the young normal-hearing adults performed better than the elderly hearing-impaired and young normal-hearing adults with a simulated hearing loss. There was, however, no difference between the two hearing-impaired groups. The authors concluded that the findings were consistent with the notion that "the primary factor underlying speech recognition difficulties on the elderly hearing-impaired is the presence of a sensorineural loss producing a loss of sensitivity and loudness recruitment for high-frequency stimuli" (Humes & Roberts, 1990, p 730).

Souza and Turner (1994) appraised word recognition performance in three competing noises among young normal-hearing, young hearing-impaired and elderly hearing-impaired participants To no surprise the hearing-impaired listeners performed worse than the normal-hearing listeners. There was, however, no difference between the young and older hearing-impaired participants, suggesting that the detriment in word recognition performance was a result of the hearing loss alone and not any age-specific factor(s)

Finally, Humes, Watson, Christensen, Cokely, Halling, and Lee (1994) measured speech recognition performance for a wide range of materials and listening conditions and in addition administered the Test of basic Auditory Capabilities (to assess auditory processing), Wechsler Adult Intelligence Scale-Revised, and Wechsler Memory Scale-Revised to 50 participants aged 63 to 83 A principal component analyses revealed two components explaining most of the variation in speech recognition performance. Audibility was the largest component accounting for approximately 75% of the variance The second factor accounted for 6% of the variance and represented recognition of speech at high intensities. The measures of cognition and auditory processing accounted for little or no additional variance.

Some investigators have suggested that the decline in speech understanding cannot be accounted for by the peripheral loss in hearing sensitivity but have failed to offer what those factor(s) may be aside from age effects (e.g., Dubno et al., 1984; Hargus & Gordon-Salant, 1995; Schum et al., 1991). Other groups of researchers have suggested that, although most of the decline in speech understanding can be accounted for by the peripheral hearing loss in presbycusic listeners, there are other less significant factors involved. For example, van Rooij and Plomp (1989, 1990, 1992) in a series of studies examined the auditive and cognitive factors contributing to speech perception difficulties in elderly listeners. A battery of tests was administrated to elderly participants including tests of audition (sensitivity, and frequency and temporal resolution), cognition (memory, processing, and divided attention), and speech reception (phoneme, spondee, and sentence level). Multivariate analyses revealed two statistically independent components accounting for the systematic variance in speech recognition performance. One component, representing two-thirds of the total variance accounted for in speech test performance, represented the high-frequency hearing loss with age while the second, accounting for the other one-third of the total variance, represented a general slowing of cognitive performance and reduced memory capacity.

Gatehouse (1991) assessed 240 individuals aged between 50 and 70 years with a battery of peripheral (i.e., hearing thresholds, temporal and frequency resolution), central auditory (i.e., binaural masking level difference, staggered spondaic words, Four Alternative Auditory Feature Test [Foster & Haggard, 1987], sentence identification in noise, and sentence identification in quiet with normal and fast presentation rates), and nonauditory cognitive (i.e., verbal and nonverbal intelligence quotient) indices A stepwise multiple regression found that 21% of the performance variance was accounted for by age and peripheral hearing loss while an additional 11% was accounted for by aspects of central auditory function. Further, "the central auditory factors themselves were poorly related to the non-auditory variables of verbal and non-verbal IQ, suggesting they play a specifically auditory role as opposed to there being generally decreased processing ability" (Gatehouse, p 182).

Humes and Christopherson (1991) reported similar results They investigated auditory processing and speech identification among young normal-hearing adults, young normal-hearing adults with a simulated hearing loss, and hearing-impaired older listeners aged 65 to 75, and hearing-impaired older listeners aged 76 to 86. A between-groups analysis on performance on the auditory processing and speech identification tasks, and a within-groups correlation and regression analyses within the two elderly groups was undertaken. The two older groups performed worse than the young normal and young simulated hearing-impaired groups The fact that the young simulated hearing-impaired group's performance was superior than the older hearing-impaired listeners suggested that audibility alone could not account alone for the poorer performance among the older participants The correlation and regression analysis suggested that the primary contributor to speech understanding performance was the hearing loss but with increasing age this was less true. That is, there was an effect of age on performance independent of hearing loss

Finally, Jerger, Jerger, and Pirozzolo (1991) administered a battery of auditory and neuropsychological tests to 200 elderly participants with various audiometric configurations. Audiometric tests included monosyllabic word recognition, Synthetic Sentence Identification ([SSI], Speaks & Jerger, 1965), Speech Perception In Noise ([SPIN], Kalikow, Stevens, & Elliot, 1977) and Dichotic Sentence Identification (Fifer, Jerger, Berlin, Tobey, & Campbell, 1983). Neuropsychological tests included the Wechsler Adult Intelligence Scale-Revised (Wechsler, 1981), three subtests of the Wechsler Memory Scale-Revised (Wechsler, 1987), Boston Naming Test (Kaplan, Goodglass, & Weintraub, 1983), Spatial Orientation Memory Test (Wepman & Turaids, 1975) Selective Reminding Test (Buschke & Fuld, 1974), and a four-choice visual reaction time test. A canonical analysis indicated two independent dimensions significantly affect speech recognition in elderly listeners The first was degree of hearing loss; the second was cognitive status. Multiple regression analyses suggested, however, that cognitive measures increase prediction of speech scores minimally and have relatively small consequence on speech measures. For example, percentage of variance accounted for after hearing loss was 6%, 3%, 6%, 8%, and 12% for monosyllabic word recognition, low predictability SPIN scores, high predictability SPIN scores, SSI, and Dichotic Sentence Identification, respectively.

Various investigators have proposed that central auditory dysfunction accompanies senescence and it is this in conjunction with peripheral hearing loss that is responsible for speech understanding difficulties. To assess peripheral and central auditory function, Otto and McCandless (1982) administered a battery of audiometric tests to two groups of 30 participants with matched hearing thresholds. One group was young hearing-impaired aged 17 to 45 years while the other was older, aged 60 to 80 years. Significant differences were found between groups for measures of both central and peripheral function. For example there was a higher incidence of recruitment, greater neural adaptation, reduced short term memory, poorer SSI scores, and abnormal auditory brainstem response indices. The authors suggested in many cases there "is behavioral and electrophysiological evidence of peripheral neural and central neural changes in the senescent auditory system" (Otto & McCandless, p. 114). The prevalence of central auditory dysfunction among individuals over 60 years of age has been estimated to range as high as 50% to 70% in clinical samples and increases dramatically with increasing age (Jerger, Jerger, Oliver, & Pirozzolo, 1989; Shirinian & Arnst, 1982; Stach, Sprentnjak, & Jerger, 1990). Interestingly, central auditory decline has been reported in cognitively intact elderly adults without a concomitant decline in hearing sensitivity or linguistic proficiency (Rodriguez, DiSarno, & Hardiman, 1990). Rodriguez et al. reported that 15 of 25 participants between 60 and 85 years of age displayed abnormal performance on the SSI-Ipsilateral Competing Message test (Speaks & Jerger, 1965).

It is the opinion of some that the decline in speech understanding in the elderly is a sole consequence of concomitant extra-auditory cognitive decline (e.g., Working Group on Speech Understanding and Aging, 1986). It has been suggested that the cognitive deficits in the elderly are a consequence of a general remission or slowing of behavior (Birren et al., 1980) or a decrease in processing speed (Salthouse, 1980). If performance on audiometric tests depends on cognitive abilities such as memory and processing speed then one does not have to embrace the concept of central auditory deficits as a culprit for speech understanding difficulties experienced by the elderly listener. The cause of impoverished speech understanding is a result of declining cognitive skills. This line of reasoning was adopted by Wingfield, Poon, Lombardi, and Lowe (1985). Time compression was used to vary speech presentation rates for normal sentences, syntactic strings, and random strings of words presented to 12 normal-hearing young (mean age = 19 years) and 12 older listeners (mean age = 67 years). Segment length (5 or eight words) was another independent variable while words correctly recalled was the dependent variable. The results included an age interaction with speech rate. There was a greater detriment in performance for more meaningless stimuli, increased speech rate, and stimulus segment length for the elderly participants. The authors suggested that the use of time-compressed materials revealed a reduction in available central processing time among the elderly participants.

Jerger and colleagues in a series of articles argue adamantly against any suggestion that a concomitant decline in cognitive ability is solely responsible for a decline in speech understanding in the elderly. In one study, 130 healthy elderly participants ranging in age from 51 to 91 years were given a battery of audiometric and cognitive tests (Jerger, Jerger, Oliver, & Pirozzolo, 1989). Test results were categorized as normal or abnormal. Sixty-three percent of cases were scored as congruent (i.e., normal-normal or abnormal-abnormal) in terms of central auditory status and cognitive status. The remaining 37% of results were incongruent That is, an abnormal categorization on one aspect was not associated with an abnormality on the other aspect In other words, the incongruent results do not support the hypothesis that a cognitive decline can alone be responsible for a decline in speech understanding. The authors argued, as well, that peripheral hearing loss was not responsible for the abnormal scores on the central auditory function indices because the central auditory tests were relatively free of dependence on audiometric level. There was also no indication that those participants that had abnormal central test scores had poorer audiometric configurations than those who scored normal on the same measures. Jerger et al concluded that "the speech understanding problems of the elderly cannot be explained as simple functions of either degree or peripheral hearing loss or degree of cognitive decline" (Jerger et al., 1989, p.89).

In a second study, Jerger, Stach, Pruitt, Harper, and Kirby (1989) investigated auditory function among 23 diagnosed dementia patients. Jerger et al. reasoned that patients who were cognitively depressed should exhibit a depressed performance on auditory measures if those measures were cognitively demanding. Twelve of the 23 participants, however, displayed normal central auditory function assessed with word recognition and the SSI Test. Such findings are inconsistent with the notion that a cognitive decline must have a significant concomitant effect on central auditory function measures. Jerger, Mahurin, and Pirozzolo (1990) also presented a case study of a 40 year old individual following a bout of viral encephalitis who presented with severe cognitive deficits (i.e., attention and speed of mental processing decline). The individual presented with a unilateral central auditory deficit. The finding was important to the researchers as a central auditory deficit was demonstrated in spite of severe cognitive deficits. In other words, the case "demonstrates that central, specifically-auditory, effects may coexist with cognitive deficits, and that the two can be measured separately" (Jerger et al., 1990, p. 119).

Finally, Jerger (1992) examined the contribution of peripheral hearing loss on speech understanding. One hundred and thirty-seven presbycusic participants aged 50 to 90 years were evaluated. They were divided into four groups matched for equivalent pure-tone thresholds: 50 to 65 years, 66 to 70 years, 71 to 75 years, and 76 to 90 years. Word recognition, SSI (Speaks & Jerger, 1965), and SPIN (Kalikow et al., 1977) tests were administered. Generally, all measures showed some reduction in performance with age. An omnibus multivariate analysis revealed a significant age effect and an age by group interaction. Individual analyses of variance by group for each speech measure revealed a significant age trend for only the SSI (i.e., a drop of 30% in scores across the four age groups was observed). Jerger suggested that the results were inconsistent with the notion that subtle changes in peripheral hearing were responsible. His reasoning was that the scores on the monosyllabic tests should have been affected more severely since cochlear status affects single syllable recognition more than sentence recognition. The results are also inconsistent with a concomitant change in cognitive status as there were no significant correlations among administered neuropyschological indices and the SSI scores.

The above review of literature suggests that speech understanding difficulties experienced by presbycusic listeners may be a consequence of peripheral hearing loss, central auditory system dysfunction, and/or cognitive deficits. There does not appear to be convincing evidence that one factor is alone responsible for the decline in performance observed. There is evidence to suggest that any one factor can exist in the absence of the others as well as being present in any combination.

Temporal Resolution in the Presbycusic Listener

Only in the last 10 to 15 years have researchers directed their attention to temporal auditory phenomena in the elderly. McCronsky and Kasten (1982) first reported clinical data on approximately 500 clients 20 to 80 years of age. They reported that their clients demonstrated increased detection intervals in an auditory fusion of two tones task particularly after the fifth decade. They also reported that response performance on rate-altered speech was differentially affected by age. Unfortunately, detailed methodology was lacking in the manuscript, and since hearing status was not reported it is difficult to determine if the detriment in performance was a function of aging or hearing loss.

Several investigators have used masking paradigms to investigate temporal resolution among presbycusic listeners. Masking period patterns, where prestimulus and poststimulus masking are presented together, were examined by Zwicker and Schorn (1982). Masking patterns were explored at 500, 1500, and 4000 Hz. Reduced temporal resolution was found only at 4000 Hz. It is likely that this pattern of performance was due to impoverished resolution in the high frequencies as a result of the loss of audibility. Newman and Spitzer (1983) utilized an auditory backward-recognition masking paradigm with 10 normal-hearing young listeners and 10 elderly listeners aged 75 to 85. The elderly participants had normal age-adjusted threshold criteria (i.e., they had hearing impairment consistent for their age) Participants identified two equi-probable test tones (i e , 770 or 870 Hz) followed by a noise masker as a function of interstimulus interval. It was reported that the elderly listeners achieved the same level of identification of the tones as the young listeners; however, they needed longer interstimulus intervals to reach and maintain equivalent performance. As the stimuli were presented at one SPL, it is difficult to discern if the performance impairment observed among the elderly participants was a function of reduced sensation level or aging. Raz, Millman, and Moberg (1990) used a similar auditory backward-recognition masking paradigm with 11 normal-hearing young listeners and 11 elderly listeners aged 61 to 80. Raz et al. employed a two-interval forced-choice, two-tone frequency discrimination array in an effort to reduce confounding effects of secondary memory for tones that may have plagued Newman and Spitzer's findings. Six target interstimulus intervals were utilized. The findings were similar to those of Newman and Spitzer in that younger listeners could escape from masking at shorter interstimulus intervals (i.e., elderly listeners were more vulnerable to the masking effects at equal interstimulus intervals). Again the findings are difficult to interpret as both groups differed on hearing sensitivity and therefore effects can not be attributed solely to aging. Finally, Cobb, Jacobson, Newman, Kretschmer, and Donnelly (1993) reported a significant increase in target thresholds, in a 500 and 4000 Hz tone/maskee wideband noise/backward masker task, as a function of aging. Thirty-three listeners ranging in age from 26 to 76 years participated. All participants had normal-hearing (i.e., thresholds ≤ 25 dB HL from 250 to 4000 Hz). The Cobb at al. results indicated a 2, 4, 8, and 11 fold difference in target threshold values from the forth to fifth, sixth, seventh, and eighth decades, respectively.

Some researchers have used auditory duration discrimination as a means to explore temporal selectivity in elderly listeners. S.L. Phillips, Gordon-Salant, Fitzgibbons, and Yeni-Komshian (1994) investigated difference limens and backward interference of difference limens for a 40 ms, 1000 Hz test tone and a comparison tone of longer duration in a three-interval forced-choice task. In one experiment, difference limens were determined for ten elderly participants aged 65 to 80 years and 10 young normal-hearing participants. All participants had hearing thresholds ≤ 20 dB HL. The older participants had on average overall poorer hearing sensitivity, however. There was no statistically significant difference between difference limens of both groups. In a second experiment, difference limens were again determined while a backward masker was introduced at three delay times of 80, 240, and 720 ms. A significant age by backward masker delay interaction was found. Younger participants' difference limens were better at the shortest delay. S.L. Phillips et al. concluded that elderly listeners have an impaired ability to process duration information when interfering stimuli are in close temporal proximity. "The findings add support to the notion that there is a slowed processing of the durational characteristics of acoustic signals in older listeners and that these age effects are revealed on tasks that increase the complexity of the stimulus paradigm" (S.L. Phillips et al., p.214). Fitzgibbons and Gordon-Salant (1994) investigated duration discrimination among young and elderly normal-hearing and hearing-impaired listeners. Difference limens were measured for tone bursts centered at 500 and 4000 Hz and for silent intervals between the bursts Results revealed that the elderly participants had greater difference limens for both gaps and tones irrespective of hearing status. Similar results have been reported by Abel, Krever, and Alberti (1990).

Lutman (1991) used gap detection to assess temporal resolution in 229 listeners aged between 50 and 75 years Gap detection thresholds for a noiseband centered at 2000 Hz were reported to increase with increasing hearing threshold, however, no effect of age was found Moore, Peters, and Glasberg (1992) reported gap thresholds in sinusoids (100, 200, 400, 800, 1000 and 2000 Hz) presented in background noise for elderly listeners with and without hearing loss Gap thresholds were similar between the two groups and most were comparable with data from younger listeners suggesting to Moore et al., as with Lutman, "reduced temporal resolution does not appear to be an inevitable consequence of aging" (p. 1923). von Wedel, von Wedel, and Streppel (1991) reported data to the contrary for listeners aged from 18 to 70 years. That is, gap detection thresholds increased significantly as a function of age. Cortical evoked potentials in response to brief gaps or an incoherence in the signal were delayed in the elderly participants. Unfortunately von Wedel et al. did not report hearing sensitivity, and as a consequence, the findings cannot be interpreted to suggest an age effect causal to impaired temporal resolution performance in the elderly participants; hearing loss may have confounded the results.

Cranford and colleagues have investigated the effects of aging on the precedence effect in sound localization. The precedence effect provides a means to examine the auditory system's ability to process binaural signals with interaural temporal disparity. The effect is achieved by delivering two identical sounds from both sides of a listener, either by loudspeaker or earphone. The presentation of one sound leads the other by a short period of time (i.e., several hundred ms). The listener's perception is a lateralization of the sound source to the side of the leading sound while apparently being unaware of the lagging sound. In other words, the multiple inputs are not temporally resolved. When the separation between the leading and lagging sound exceeds a particular value, the listener perceives both sounds (i.e., they are temporally resolved). Thresholds, for the precedence effect, are defined by the value at which below the delay interval, listeners responds only to the leading sound while above they respond to both. In the group's first study (Cranford, Boose, & Moore, 1990), two groups of 24 young (aged 20 to 46 years) and elderly (aged 62 to 78 years) participants were examined. It was found, that for pairs of clicks presented from loud speakers, the elderly participants were poorer in correctly identifying the leading click sound for delays less than 0.7 ms. There was no significant correlation between participants' high-frequency pure-tone average and precedence performance. In a subsequent study (Cranford & Romereim, 1992), performance-intensity functions for monosyllabic words and scores on the SSI (Speaks & Jerger, 1965) and precedence test values were compared among young and elderly participants. Findings with the precedence test performance paralleled those of the first study: there was no difference between the two groups with delays greater than 0.7 ms and there was no significant correlation between participants' high-frequency pure-tone average and precedence performance. The rollover indices for the monosyllabic words and SSI test were larger for the elderly participants. The SSI maximum performance and precedence performance were significantly correlated and the former was also not correlated with high-frequency pure-tone average. The authors conclude that age-related speech understanding difficulties may be a consequence of impaired temporal acuity.

In a series of experiments, Trainor and Trehub (1989) investigated the ability to order sequences of tones as a function of presentation speed and streaming context in two groups of 16 young (mean = 21 years) and elderly listeners (mean = 69 years). Two repeating sequences of four tones differing in order served as stimuli. In the first experiment listeners were required to identify the sequence. A second experiment required listeners to make a same or different judgment for two successive pattern presentations. In the third experiment, participants practice effects on performance were evaluated. In the final experiment, participants had to identify two four tone patterns that did not have a recycled pattern. The four tones varied in frequency by 178 Hz. In general, the findings showed "elderly adults were less able than young adults to distinguish between sequences with contrasting orders, regardless of the speed of presentation, the nature of the task (identification vs. same/different), the amount of practice, the frequency separation of the tone, or the presence or absence of recycling" (Trainor & Trehub, 1989, p.417). Further, since there was no age by presentation speed interaction, the authors suggested "the presence of a specific age-related deficiency in temporal order discrimination that is independent of stream organization" (p.423). This type of temporal sequencing deficit was speculated to be related to speech understanding difficulties exhibited by elderly listeners.

Price and Simon (1984) examined the perception of temporal differences in speech by two groups of 10 normal-hearing young adults aged 17 to 23 years and older adults aged 61 to 73 years. Naturally-produced tokens of /ræbɪd/ were edited to create a vowel and silent duration continua. That is, the voiced closure interval in the original token was replaced with four silent durations (35, 65, 95, and 125 ms) and the duration of the preclosing voiced /æ/ was manipulated to create four durations (160, 180, 200, and 220 ms). The manipulation of the preceding vowel duration and consonant closure duration was undertaken to create intervocalic stop consonant linguistic distinctions. The voicing distinction is signaled by this temporal information and separates the pairs of words /ræbɪd/ and /ræpɪd/. The shorter vowel and longer closure duration characterize /ræpɪd/ while the longer vowel and shorter closure characterize /ræbɪd/. The silent durations and vowel durations created were within the range of naturally produced productions of the two words. Sixty four stimuli incorporating all vowel and silent closure combination were created from four original tokens. Stimuli were presented monaurally to the participants at 60 and 80 dB HL. Participants responded if they heard either /b/ or /p/. Crossover points were established for an interpolated silent duration of 50% /p/ responses for each vowel duration. An analysis of variance revealed a main effect of age, an age by intensity interaction, and age by vowel duration interaction That is, the older participants needed longer silent durations before responding /ræpɪd/ and this was particularly the case with shorter vowel durations and with the higher presentation level. It was concluded 'that age may affect the relative salience of different acoustic cues in speech perception, and that age-related hearing loss may involve deficits in the processing of temporal information, deficits that are not measured by standard audiometry" (Price & Simon, 1984, p. 405).

Temporal processing ability as assessed by modulation detection and modulation masking (a task demanding temporal envelope processing) was studied by Takahashi and Bacon (1992). Four groups of 10 listeners were employed: older listeners in each of three age groups, 50 to 59, 60 to 69, and 70 to 76 years of age plus normal-hearing young adults. All of the older participants had hearing losses characteristic of presbycusis In the first experiment, modulation detection thresholds were obtained for a broadband noise for modulation frequencies between 2 and 1024 Hz. The older listeners were less sensitive to amplitude modulation; however the differences did not attain statistical significance. In the second experiment, the signal was amplitude-modulated at 8 Hz and presented in a 100% modulated masker ranging in modulation frequency from 2 to 64 Hz (i.e., modulation masking). Only the participants in their seventies displayed significantly poorer performance than the younger normal-hearing group The final experiment explored sentence understanding in broadband noise that was either amplitude-modulated or unmodulated. The speech signal was set at 70 dB SPL while the noise was manipulated to obtain S/Ns of 12, 8, 4, 0, -4, and -8 dB. An analysis of variance revealed main effects of age group, S/N, and background condition and a significant S/N by background interaction. That is, participants performed better in the modulated background, participants performed better at higher S/Ns, the young listeners performed better than the older listeners, and the interaction reflected the fact that performance in the two background conditions tend to merge at favorable S/Ns. Takahashi and Bacon attributed the difference in performance between the young and older participants to differences in hearing sensitivity and not age per se. They concluded, based on the performances found in the three tasks, there were no significant effects of aging when hearing sensitivity was taken into account.

Gordon-Salant and Fitzgibbons (1993) investigated the effects of speech recognition with temporal waveform distortion. Low-predictability sentences from the SPIN test were presented undistorted and distorted by time compression, reverberation or interruption. Four groups of participants were evaluated: young normal-hearing, young hearing-impaired, older normal-hearing, and older hearing-impaired. The etiology of the hearing loss in the older participants was presbycusis. They ranged in age from 65 to 76 years. Both normal-hearing groups had pure-tone thresholds ≤ 15 dB HL. The hearing-impaired groups were matched for hearing sensitivity and word recognition performance in quiet. There were four degrees of distortion for each type of distortion: time compression at 30%, 40%, 50%, and 60%; reverberation at 0.2, 0.3, 0.4, and 0.6s; and interruptions at 12.5, 25 , 50, and 100/s. Analyses of percent correct speech recognition scores revealed that significant effects of age independent of the hearing loss on all three temporally distorted speech tasks. Younger participants performed better even when possible performance differences in the undistorted condition were covaried out. Gordon-Salant and Fitzgibbons concluded that the findings are consistent with the fact that age-related factors other than reduced hearing sensitivity contribute to impaired speech understanding in presbycusic listeners.

In summary, the overwhelming majority of studies have revealed poorer performance on tasks revealing auditory temporal phenomena among presbycusic participants. There is less agreement as to the nature of the deficit. That is, are the performance detriments observed a consequence of the peripheral loss in hearing sensitivity or are there other age-related factors that also contribute independently? A number of studies comparing young and elderly listeners failed to control for differences in peripheral hearing status and can be dismissed. Other, more well-controlled studies have reported equivocal results. Some researchers have suggested that methodological variations contribute to the discrepant findings. Specifically, some measures may be more sensitive in revealing age-related changes independent of peripheral hearing sensitivity because the employed paradigm(s) stress the auditory system more by being perceptually more demanding (e.g. Gordon-Salant, 1987; Humes & Roberts, 1990; Souza & Turner, 1994; Takahashi & Bacon, 1992).

Employing the Interrupted Noise Paradigm with Presbycusic Listeners

It was concluded above that the interrupted noise paradigm could reveal auditory temporal phenomena. Adequate temporal resolution is required as the listener must sustain the temporal gaps in the masker thereby taking advantage of the favorable S/Ns. The release from masking in interrupted noise must be limited by the auditory system's ability to resolve acoustic information in the silent gaps between the successive noise bursts. D.P. Phillips et al. (1994) originally suggested, with listeners suffering from noise-induced cochlear pathology, that a specifically temporal deficit in the cochlea could be independently demonstrated. They offered that the performance deficit displayed by noise-induced hearing-impaired listeners was a result of reduced available bandwidth. That is, "if listeners normally use high-frequency cochlear output channels for the detection of transient stimulus amplitude fluctuations ... and those channels are rendered insensitive by pathology, then the temporal deficit might be the consequence of the hearing-impaired listener being forced to use only low-frequency cochlear output channels" (D.P. Phillips et al., p. 684). It stands to reason that listeners suffering from presbycusis should display a similar performance deficit in interrupted noise relative to normal-hearing listeners. That is, if inferior performance is related to restricted listening bandwidth, specifically a loss of high-frequency cochlear output channels that have the best temporal resolution, then listeners with presbycusis should display performance detriments as their audiometric configuration is typically a high-frequency sloping cochlear loss.

Word recognition and repetition involve processing on multiple levels (e.g., Phillips, 1995). Maskers with time-varying envelopes are speculated to be more sensitive in revealing deficits in speech understanding in noise. The deficits revealed need not necessarily be peripheral in nature. This has been confirmed by two independent sources. Middelweerd, Festen, and Plomp (1990) examined a group of 15 individuals with complaints of speech understanding in noise. Their hearing sensitivity was normal and otological history unremarkable. Speech reception thresholds for sentences were examined in steady state and fluctuating masking noise. The latter noise had a modulation waveform equivalent to running speech. Performance in fluctuating noise revealed the greatest difference between the patient group and a normal control group. Middelweerd et al. suggested that the performance difference observed in the fluctuating noise with the patients was a consequence of an inability to utilize the periods in the fluctuations in which speech is present at more favorable S/Ns; that is, wanting temporal resolution. As the participants peripheral auditory function was normal, as revealed by pure-tone thresholds and word recognition in quiet, one could suggest that the nature of the deficit as revealed in their performance in fluctuating noise must be "central" in nature. This is assuming that normal pure-tone thresholds and word recognition performance in quiet truly reflect normal peripheral auditory function.

In another study, Rappaport, Gulliver, Phillips, Van Dorpe, Maxner, & Bhan (1994) evaluated 12 patients with multiple sclerosis confirmed by magnetic resonance imaging. All 12 patients had demyelinating lesions in the auditory system: seven with lesions in the rostral auditory fiber tracts and the remaining five with lesions restricted to the auditory brainstem. All patients displayed essentially normal-hearing sensitivity to 4000 Hz. Five patients had mild losses at 6000 and/or 8000 Hz. Patients were assessed with a battery of audiometric tests including the D.P. Phillips et al. (1994) interrupted noise paradigm (i.e., word recognition performance-intensity functions in continuous and interrupted broadband noise). The patients suffering from multiple sclerosis displayed equivalent performance relative to normal-hearing young adults under the continuous noise; however, the performance in the interrupted noise was significantly impaired. The researchers conclude this pattern of performance was consistent with a temporal processing deficit Again, as the patients' peripheral auditory function was normal, one can conclude that the deficit has to be central in nature Considering the findings of D P. Phillips et al and Rappaport et al , one may suggest that the interrupted noise paradigm can expose temporal resolution deficits of various etiologies, both peripheral and central in nature.

This lat r observation seems intriguing considering the nature of the temporal defi observed in presbycusis That is, several researchers have suggested that performance detriments observed on temporal resolution tasks may be a consequence of other age-related factors that contribute independently from the peripheral hearing loss in presbycusic listeners (e g., Fitzgibbons & Gordon-Salant, 1994, Gordon-Salant & Fitzgibbons, 1993, S L Phillips et al., 1994, Price & Simon, 1984) It appears that the interrupted noise paradigm may be employed to reveal not only expected deficits in temporal processing associated with the peripheral hearing loss in presbycusic listeners but also any deficit that may be a consequence of central factors independent of the peripheral pathology.

To address this speculation it was proposed that the word recognition in noise paradigm developed by D P. Phillips and colleagues (D.P Phillips et al , 1994; Rappaport et al., 1994) be employed. Specifically, in a second experiment of this dissertation, performance-intensity functions for word recognition in continuous and interrupted broadband noise as a function of S/N were examined between young normal-hearing adults, cognitively-intact older normal-hearing adults, and cognitively-intact age-matched presbycusic adults. It was speculated that performance differences revealed by this quantitative speech-in-noise paradigm could reveal the contribution of any peripheral and central temporal resolution deficits towards word recognition performance. That is, performance differences between the young normal-hearing adults and elderly normal-hearing adults may reflect aging per se while the performance differences between the elderly normal-hearing adults and elderly hearing-impaired adults may reflect presbycusis per se.

Two additional studies were also proposed. In their previous studies D.P. Phillips et al., (1994) and Rappaport et al. (1994) employed either 40 or 50 SL presentation levels for the monosyllabic stimuli and varied the noise stimuli levels around those levels. As many hearing-impaired listeners often suffer from loudness recruitment, it was deemed that such presentation levels would be intolerable for the presbycusic listeners. This would be undoubtedly true in the adverse S/Ns (i.e., -15 and 20 dB). It was submitted that normative data needed to be generated at a lower sensation level of presentation. A third experiment of this dissertation addressed this concern and compared young normal listeners performance in continuous and interrupted noise at two sensation levels. The final experiment addressed the notion of "normal" hearing older listeners. What constitutes a normal-hearing elderly listener has been a concern for many (e.g., Gordon-Salant, 1987; Marshall, 1981; Working Group on Speech Understanding and Aging, 1988). Numerous researchers have employed normal-hearing elderly listeners. The typical operating definition for normal-hearing elderly listeners is that they require pure-tone hearing thresholds of ≤ 25 or 20 dB HL (e.g., Cobb et al., 1993; Fitzgibbons & Gordon-Salant, 1994; Gordon-Salant & Fitzgibbons, 1993; S.L. Phillips et al., 1994). Clearly many studies have ignored hearing sensitivity at frequencies above 4000 Hz. The most obvious reason is practical: virtually all elderly listeners have some loss of hearing sensitivity above 4000 Hz. To insist on hearing thresholds within a normal range to 6000 or 8000 Hz would preclude the overwhelming majority of older individuals. Yet when one observes performance differences between normal-hearing young adults and normal-hearing older adults, the question that begs to be answered is "Are these performance differences a reflection of age per se or differences in hearing sensitivity above 4000 Hz?" The final experiment addressed this issue subsequent to findings in the third experiment

Chapter 1

Word Recognition Performance in Continuous and Interrupted Broadband Noise by Normal-Hearing and Simulated Hearing-Impaired Listeners

In this study, it was hypothesized that a listener's performance on a temporal resolution task should be governed by the functional capacity of the high-frequency region of their cochlea since this is the population of high-frequency cochlear output channels that has the best temporal resolution. Specifically, normal-hearing participants should exhibit a detriment in performance akin to that of hearing-impaired listeners if listening is relegated to low-frequency channels that have inherently inferior temporal resolution. If that is the case, one would predict that normal-hearing listeners, with a simulated high-frequency hearing loss, should display comparable patterns of impaired performance on the same task as that employed by D.P. Phillips et al. (1994). If such a performance deficit is found, then one may conclude that the hearing-impaired listener's performance is attributable to their selective use of low-frequency cochlear channels, which may well be normal, but have poorer temporal resolution. If a performance deficit is not evident then one must conclude that abnormal temporal processing found with hearing-impaired listeners must be a consequence of their continued use of the impaired sector(s) of the cochlea. The purpose of this study was to investigate this speculation by comparing normal-hearing participants' performance in continuous and interrupted broadband noise as a function of S/N with and without a simulated high-frequency hearing loss.

Method

Participants

Twelve young adult university undergraduate and graduate students (*M* = 23.8 years, *SD* = 1.8; three males and nine females) served as participants. All participants presented with normal-hearing sensitivity defined as having pure-tone thresholds at octave frequencies from 250 to 8000 Hz and speech reception thresholds (SRTs) of ≤ 25 dB HL (American National Standards Institute, 1989). The group mean SRT was 6.7 (*SE* = 1.4). As well, all participants presented with normal middle ear function (American Speech-Language-Hearing Association, 1990).

Stimuli

The test stimuli consisted of custom two channel stereo cassette tape recordings of lists one to four of the Northwestern University Auditory Test No 6 (NU-6). The stimuli contained in each NU-6 list were 50 monosyllabic words having a consonant-nucleus-consonant construction. They are based on stimulus items originally developed by Lehiste and Peterson (1959) Initially. the Northwestern University Auditory Test was comprised of two lists (Tillman, Carhart, & Wilber, 1963). However, it was later expanded to four 50 word lists (Tillman & Carhart, 1966) employed in this study. The competing stimuli were continuous or interrupted broadband noise.

The custom recordings were developed by first transferring compact disk female talker recordings of the NU-6 lists (Department of Veterans Affairs, 1989) onto an IBM compatible computer's (Zenith Model Z-386/20) hard drive via a compact disk player (Sony Model 608ESD) interfaced with an analog input/output board (Dalanco Spry Model 250). The word lists were then edited to remove the carrier phrase and to reduce the interstimulus intervals from 4.2 to 3.0 s.

The competing continuous broadband noise was generated by the computer. A 10 s segment of the noise file was examined using signal processing software (Signal Technology Inc. Model Interactive Laboratory System V6.1) to confirm that the noise spectrum was "flat" within two dB from 100 to 8000 Hz. A copy of the broadband noise file was then interrupted, employing a rectangular on/off envelope such that the durations of the noise bursts, and of the silent periods between them, were varied randomly from 5 to 95 ms, to create the interrupted noise stimuli. The temporal duration of the noise was selected to mimic the acoustic elements of speech (i.e., several ms to tens of ms representative of consonant bursts to steady state vowels, respectively). The randomization of the gating of the noise was chosen to eliminate any pitch percept that may possibly arise from periodic modulation of the masker which may be employed as a cue to segregate signal and noise by the listener. The noise time-fraction (i.e., the proportion of time occupied by the noise) for the interrupted noise files was 0.50. All speech and noise files were then normalized to have equal power.[2] Two calibration tones were then generated, one at full scale and the other at the normalized power level (i.e., 0 dB signal-to-noise level). The full scale calibration was utilized to ensure no overloading within the recording/playback chain.

As the software with the analog input/output board only permitted single channel recording and playback, the process of playback from the computer and recording onto tape was automated using a time-code based recording signal to ensure synchronization of the speech and noise files. Two video cassette recorders (VCRs) were employed (Panasonic Models PVS 4960 and AG-1960): The first recorded the noise files and the second was used to combine the noise and speech files. A time-code synchronization signal was first recorded onto both channels of the first VCR. That VCR was set to play back the tape, with the time-code signal to the computer. The computer in turn used the signal to precisely control the playback of the noise files. The time-code signal was then recorded from the first VCR onto the right channel of the second VCR while the noise was recorded from the computer onto the left channel. The process was then repeated to combine the speech and noise files. The second VCR was set for playback, with the time-code signal from the right channel sent to the computer with the noise files from the left channel recorded onto the left channel of the first VCR. The computer again used the time-code signal to control the playback of the speech files, which were recorded onto the right channel of the first VCR. The resulting final tape, recorded by the first VCR, was a synchronized combination of speech and noise files on separate channels. This final VHS tape was employed to produce cassette tape copies for experimental use.

All editing, noise generation and interrupting, signal power measurement and normalization, calibration tone generation, and time-code automated playback from the hard disk was accomplished with custom software. The sampling frequency for all these computer based operations was 20000 Hz giving an effective bandwidth of 8000 Hz.

To ensure that signal levels were maintained during recording onto the cassette tapes, the VCRs and recording stereo cassette tape deck (Sony Model TC-K81) were calibrated in terms of level and frequency response. Recording levels were set using the full scale calibration tone to prevent overload. No noise reduction systems were used on the cassette deck.

Examples of the amplitude envelope of a NU-6 word stimulus, continuous broadband, and interrupted noise are given in Figures 2 to 4 respectively. Digital 16-bit samples were obtained by transferring portions of the cassette tape recordings onto a personal computer's (Apple Model Quadra 700) hard drive via a stereo cassette deck (JVC Model DD-V7) interfaced with an analog to digital input/output board (Digidesign Model Audiomedia NuBus).

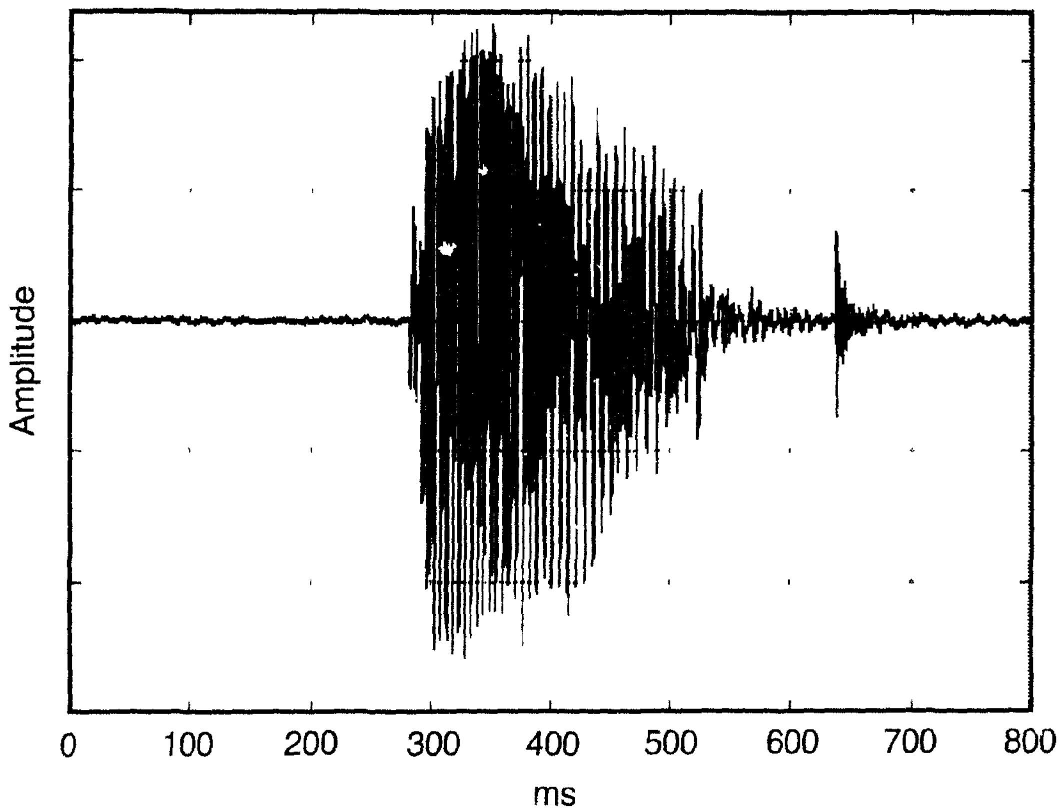

Figure 2: Amplitude waveform of the consonant-vowel-consonant NU-6 stimulus /bot/.

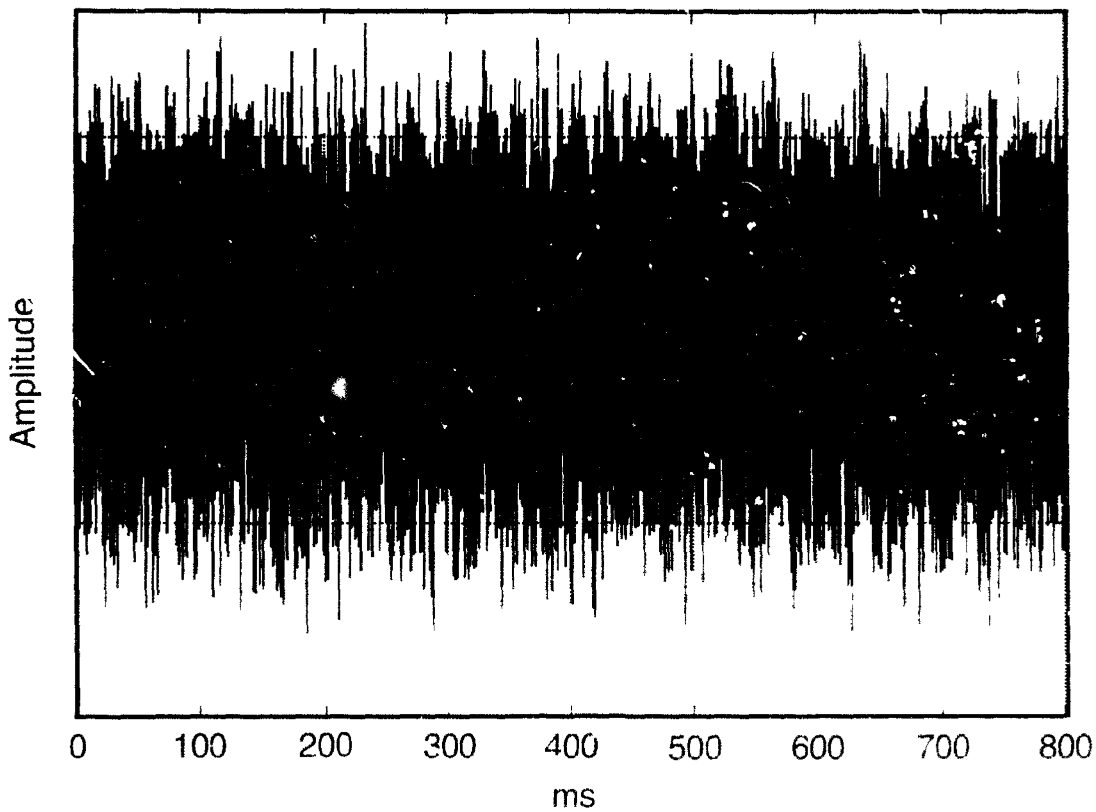

Figure 3: Amplitude waveform of a continuous broadband noise sample.

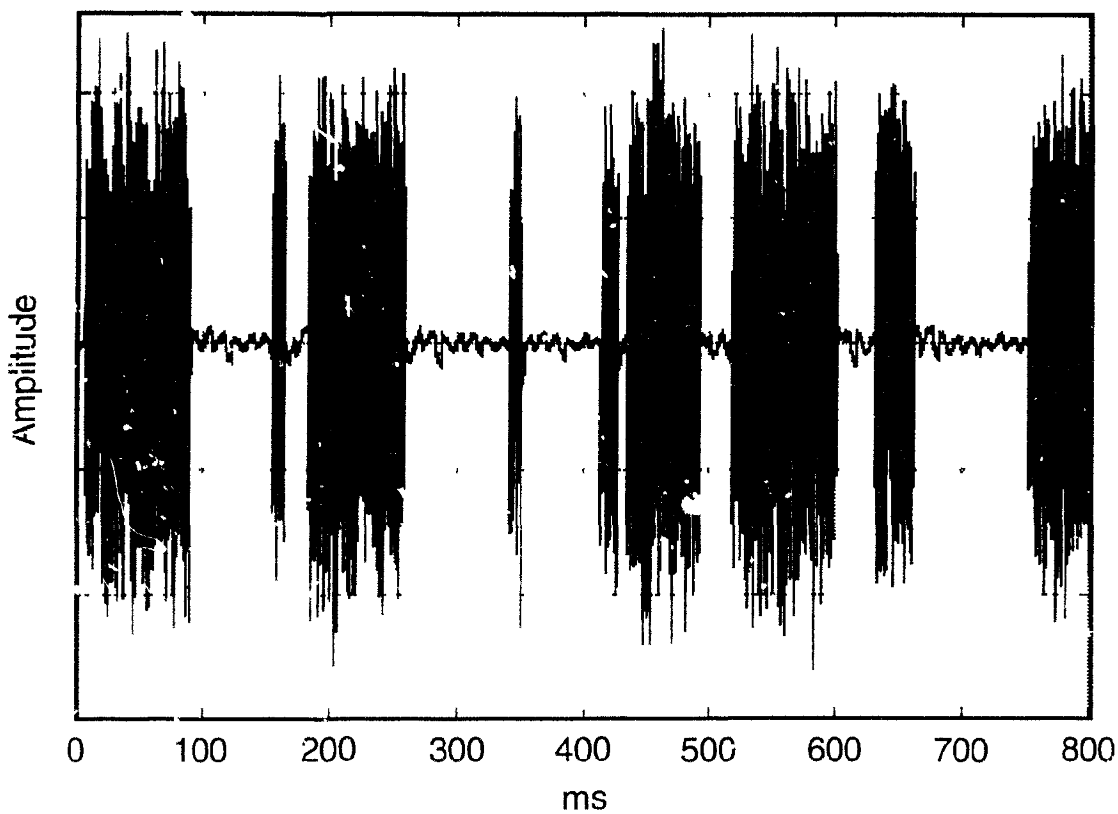

Figure 4: Amplitude waveform of an interrupted broadband noise sample.

Sampling frequency was 22050 Hz The amplitude envelopes were generated by a commercially available speech and sound signal analysis program (IntoSignal Inc. Model Signalyze 3 0) A Fast Fourier Transfer spectral analysis of the noise samples was also undertaken Samples were routed in series from the same stereo cassette deck and computer to an amplifier (Yamaha Model AX-630) and an insert earphone (Etymotic Research Model ER-3A) The earphone was coupled with 15 mm of # 13 thick-walled tubing and an ear-level hearing aid adapter to a standard 2 cm^3 HA-2 coupler A Fonix 6500 Hearing Aid Test System (Frye Electronics) was employed to measure 2 cm^3 coupler output. Noise samples were captured in real time employing the system's 16 sample noise reduction capability Sampling was obtained between 200 and 8000 Hz in 100 Hz steps It was assured that the 2 cm^3 coupler output in that range exceeded the noise floor of the system (approximately 50 dB SPL) Digital hard copies of the data were obtained Two samples of each noises were collected and averaged The root-mean-square amplitude of the continuous and interrupted broadband noises are displayed in Figure 5 As evident in Figure 5, the amplitude spectra of the noises are essentially equivalent

Apparatus

A double wall sound-treated audiometric suite (Industrial Acoustics Corporation), meeting specifications for permissible ambient noise (American National Standards Institute, 1977) served as the test environment The recorded stimuli were routed from a stereo cassette deck (AKAI Model GX-R66) to a clinical audiometer (Grason Stadler GSI 10 Model 1710-9700) and presented to each participant through an insert earphone (Etymotic Research Model ER-3A) All noise reduction and filter systems on the stereo cassette deck were in the off position during testing

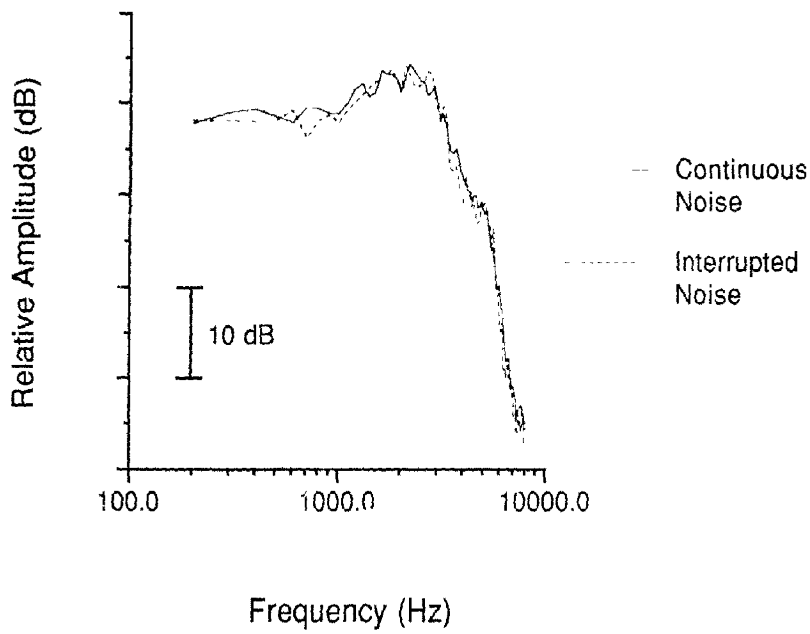

Figure 5: Root-mean-square amplitude spectra of the continuous and interrupted broadband noise, as a function of frequency (Hz), delivered to a 2 cm^3 HA-2 coupler from an insert earphone.

During the filtered listening conditions (i.e , simulated hearing-impairment) the recorded stimuli were routed from the cassette deck through a passive analog filter (Krohn-Hite, Model 3340) prior to input into the audiometer The signal was lowpass filtered, at 2000 Hz with a rolloff slope of 48 dB/octave, to simulate a high-frequency hearing loss. This choice of filter cutoff and rolloff slope was employed in an effort to mimic the "mean" audiometric configuration of the listeners used by D.P. Phillips et al (1994)

Procedure

Testing was undertaken in two separate sessions separated for logistic reasons by several months. During both sessions participants were presented with the identical NU-6 stimuli at 50 dB SL re· their respective SRTs The speech stimuli were presented in quiet and in both noise (continuous broadband and interrupted) conditions with S/Ns of 10, 5, 0, -5, -10, -15, and -20. In the first test session participants listened in the unfiltered condition while in the second session they listened in the lowpass filtered condition (i.e., simulated high-frequency hearing loss) The presentation order of lists, noise condition, and S/N was determined with a Latin square design. All test stimuli and noise competitors were presented monaurally to the participants' right ear Participants were presented with the identical NU-6 stimuli in both test sessions Instructions to participants in this and subsequent experiments are found in the Appendix.

Results

Participants' responses were scored as total whole word percent correct. Mean word recognition performance in quiet was 93.2 % (*SE* = 0 97) and 86.8 % (*SE* = 1.9) for the unfiltered and filtered listening conditions respectively. Mean scores as a function of noise type, filtered versus unfiltered condition (i e , simulated hearing loss vs. normal listening), and S/N are shown in Figure 6 As

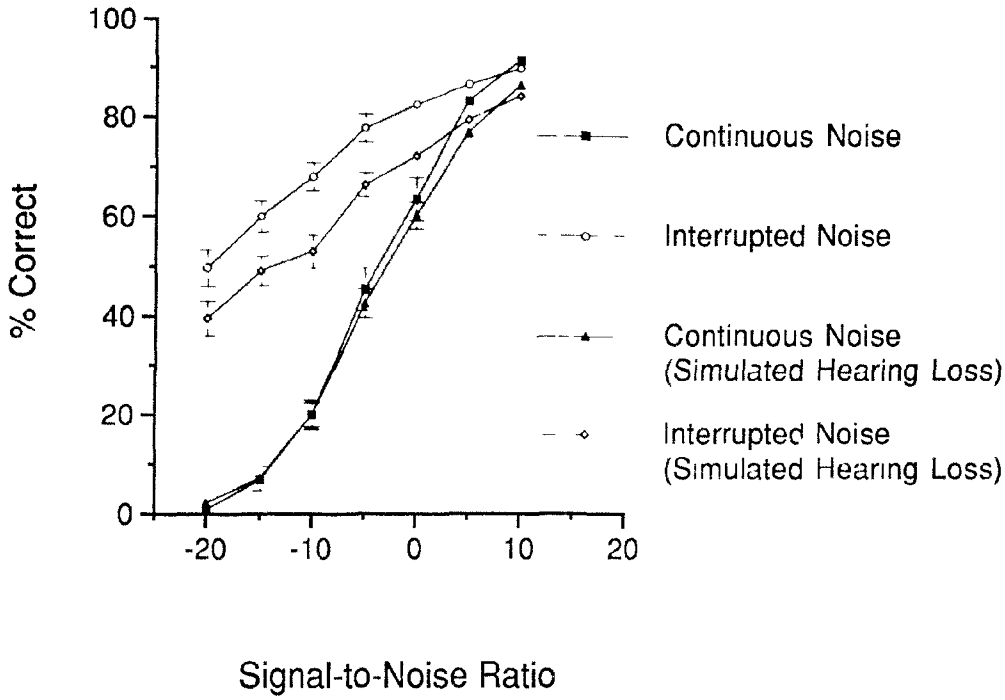

Figure 6: Mean percent correct word recognition score in continuous and interrupted broadband noise as function of Auditory Condition (i.e., unfiltered and simulated hearing loss via lowpass filtering at 2000 Hz) and S/N (n =12). Error bars represent plus/minus one standard error of the mean.

evident in Figure 6, participants exhibit typical sigmoid performance-intensity functions for the continuous and filtered continuous noise conditions In contrast, participants demonstrated shallower performance-intensity functions in the interrupted noise conditions with overall superior performance under adverse S/Ns relative to the continuous noise conditions

The participants' proportional scores were transformed to "rationalized" arcsine units (Studebaker, 1985) prior to subjecting them to inferential statistical analyses This simple linear arcsine transformation is recommended as "proportional data are not well suited to inferential statistics because the means and the variances of such data are correlated" (Studebaker, p 461) Rationalized arcsine units (RAUs) are more attractive than arcsine units as the former are numerically closer to the original percentage values while at the same time retain all of the desirable statistical properties of the latter

With respect to mean word recognition performance in quiet a statistically significant difference was found between the two groups, $t(11) = 3.07$, $p = .011$ That is, word recognition performance in quiet was superior in the unfiltered condition versus the filtered condition Separate two factor within subjects analyses of variances (ANOVAs) were undertaken to investigate mean word recognition performance differences as a function of Auditory Condition (i e., filtered vs unfiltered listening) and S/N for both continuous and interrupted broadband noise conditions The results of each separate ANOVA are presented in Tables 1 and 2 Not surprisingly, a significant main effect was observed for S/N with both continuous broadband and interrupted oise conditions ($p < .05$) In other words, irrespective of noise condition, performance increased with increases in S/N As the effect of S/N on word recognition performance is well established, no additional post hoc analysis of the main effect was undertaken. A significant main effect for Auditory Condition

Table 1

Summary table for the two-factor within-subjects ANOVA investigating word recognition performance in continuous broadband noise as a function of Auditory Condition (i.e., unfiltered vs. filtered listening) and S N.

Source	Sum of Squares	*df*	Mean Square	*F*	*p*	$\hat{\omega}^2$
Auditory Condition	218.97	1	218.97	2.41	.149[a]	.056
Error	998.89	11	90.81			
S/N	221080.66	6	36846.78	348.81	.0001*[b]	.96
Error	6972.00	66	105.64			
Auditory Condition X S/N	642.24	6	107.04	2.15	.0591[c]	.039
Error	3286.17	66	49.79			

Note. *p* values following a Geisser-Greenhouse and Huynh-Feldt correction are [a].149, .149; [b].0001, .0001; and [c].114, .0875 respectively.

* considered significant at $p < .05$.

Table 2

Summary table for the two-factor within-subjects ANOVA investigating word recognition performance in interrupted broadband noise as a function of Auditory Condition (i.e., unfiltered vs filtered listening) and S N

Source	Sum of Squares	*df*	Mean Square	*F*	*p*	ω^2
Auditory Condition	4687.37	1	4687 37	31 05	.0002*[a]	.56
Error	1660.80	11	150 98			
S/N	36925.52	6	6154.25	87 44	.0001*[b]	86
Error	4644.97	66	70.38			
Auditory Condition X S/N	187.93	6	31 32	85	.533[c]	.00
Error	2419 49	66	36 66			

Note. *p* values following a Geisser-Greenhouse and Huynh-Feldt correction are [a].0002, .0002; [b].0001, .0001; and [c].484, .518 respectively.

* considered significant at $p < .05$.

was only observed in the interrupted noise ($p < .05$). That is, superior performance was exhibited for the interrupted versus the filtered interrupted noise condition while no difference in performance was found between the continuous and filtered continuous noise conditions. No interactions of main effects were significant in either noise condition ($p > .05$). Relative treatment magnitude sizes[3] (i.e., the proportion of variation "explained" or "accounted" for by the independent variable) are indexed in both Tables by partial omega squared ([$\hat{\omega}^2$] Keppel, 1991, Keren & Lewis, 1979)[4]

Discussion

This study demonstrates that normal-hearing listeners perform differently under conditions of continuous and interrupted broadband noise. Further, a detriment in performance among normal-hearing listeners with a simulated high-frequency hearing loss was only manifested in the interrupted noise condition. The performance of the normal participants in the filtered (i.e. simulated hearing loss) and unfiltered conditions parallels D.P. Phillips et al. (1994) findings with their noise-induced hearing loss and normal-hearing groups respectively. These findings are also consistent with previous reports documenting normal listeners' improved speech understanding performance in an interrupted noise condition (Calearo et al., 1962; Dirks et al., 1969; Howard-Jones & Rosen, 1993; Miller, 1947; Miller & Licklider, 1950; Pollack, 1954, 1955; Punch, 1978; Wilson & Carhart, 1969) and with NU 6 stimuli and other phonetically-balanced word lists in continuous broadband noise with similar S/Ns (Keith & Talis, 1972; Humes, Bess, & Schwartz, 1978; Olsen, Noffsinger, & Kurdziel, 1975; Rintelmann, et al., 1975; Rupp & Phillips, 1969; Rupp, Phillips, Briggs, Rossman, Goldsmith, Rosner, & Doyle, 1977; Schwartz, Bess, & Larson, 1977; Wilson, Caley, Haenel, & Browning, 1975). In other words, the expected release from masking was observed for the interrupted broadband noise relative to continuous broadband noise masking

The findings of a slight, albeit statistically significant, detriment in performance in the filtered versus unfiltered listening condition in quiet is consistent with the effects of lowpass filtering on the intelligibility of speech (Egan & Wiener, 1946; French & Steinberg, 1947; Pollack, 1948). It is somewhat surprising that the filtered listening performance in the continuous noise was not significantly worse than the unfiltered condition Several studies have reported a loss of speech intelligibility in noise with lowpass filtered listening among normal hearing listeners (e g., Aniansson, 1974, Egan & Wiener; Pollack) The dissimilarity of this study may be a consequence of different filtering characteristics (i e , slope and cutoff frequency) and/or differences between speech material languages For example compare mean percent correct scores of 94 and 74% from Aniansson for a S/N of 0 dB with continuous noise with unfiltered and filtered listening versus 64% and 63% from this study Aniansson employed Swedish participants and utilized a 2300 Hz lowpass filter cutoff having a slope of 24 dB/octave.

D P. Phillips et al (1994) originally hypothesized that performance superiority in the interrupted noise conditions reflected listeners' ability to resolve auditory information in the gaps between the noise bursts. This notion has been expressed before. "Intelligibility remains high even at very unfavorable S/N ratios, since the listener is apparently given sufficient *looks* .. in the intervals between noise bursts" (Dirks et al., 1969, p 904) This explanation seems plausible as the competing continuous broadband and interrupted noise signals are virtually identical in spectral content and differ only in their temporal envelope characteristics. It was hypothesized that if the D.P Phillips et al paradigm does indeed tax temporal resolving capacities, listeners with impoverished temporal resolution should exhibit a decrement in performance relative to normal listeners in the interrupted noise. This was, in fact, demonstrated with the participants in this study, who as a consequence of lowpass filtering should demonstrate reduced temporal resolution, and by D.P. Phillips et al., with hearing-impaired participants, who as a consequence of their high-frequency elevated thresholds, should demonstrate reduced temporal resolution. These similarities between normal listeners with a simulated hearing-impairment and hearing-impaired listeners suggest that both groups are handicapped by being compelled to use exclusively their low-frequency auditory channels which have inherently poorer temporal resolution. This finding is consistent with previous findings that show that normal-hearing participants, with simulated hearing losses, perform on temporal resolution tasks comparably with hearing-impaired participants (Arlinger & Dryselius, 1990; Bacon & Viemeister, 1985; Buus & Florentine, 1985; Humes, 1990). This hypothesis is even more convincing when one considers that there were no performance differences in the continuous broadband noise condition between the normal-hearing participants with and without a simulated hearing loss in this study and between normal and noise-induced hearing loss participants in the D.P. Phillips et al. study.

One may argue that the findings of between group listening performance differences may be understood without needing to invoke temporal resolution per se. They may be explained as a consequence of lost audibility in the spectral domain (B.C.J. Moore, personal communication, July 25, 1995): In the unfiltered listening condition performance in continuous noise worsens as S/N worsens. This is a consequence of the high frequency followed by the middle and low frequency components of the speech signal being masked. For the filtered listening condition, performance in continuous noise is slightly impaired at the highest S/Ns as a consequence of a loss of high-frequency audibility (see Figure 6). Performance converges to that of the unfiltered listening when S/N worsens and proceeds to decrease as the middle and low frequency components of the speech signal become masked. In the interrupted noise, performance in both the filtered and unfiltered listening conditions is superior due to "glimpsing" in the interruptions of noise. The performance in the filtered listening condition is poorer as the high frequencies are inaudible. The deficit produced by this filtering is relatively independent of S/N. The middle and low frequency components may still be glimpsed. The fact that lowpass filtering does not impair performance to a greater degree suggests that temporal resolution is as good at the middle and low frequencies.

Although the argument has some intuitive appeal it appears flawed First, in the filtered listening condition, performance in continuous noise is not impaired at the highest S/Ns nor does it converge to that of the unfiltered listening at lower S/Ns (see Figure 6). The reality is that the ANOVA failed to reveal a main effect of Auditory Condition or an Auditory Condition by S/N interaction. To talk about separate data points outside of the analysis and draw conclusions is conjecture. If one were to suggest filtered listening performance 'as governed by reduced audibility in the high frequencies then two patterns hould emerge: Performance, relative to unfiltered listening, should be impaired at the highest S/Ns and then converge as S/N worsens. This would be a result of high frequency components of the speech signal being ina ible initially (from lowpass filtering) followed by masking of the middle then low frequency components as S/N worsens. This should be the case for both noise conditions. Such a behavioral pattern would be reflected in significant main effects of Auditory Condition and S/N along with an Auditory by S/N interaction being revealed by the ANOVA for both noise conditions This was not the case with the present data. As such, one is compelled to accept the argument that participants in this study, as a consequence of lowpass filtering, demonstrated reduced temporal resolution as they were obliged to use exclusively their low-frequency cochlear channels which have inherently poorer temporal resolution.

Chapter 2

Word Recognition Performance in Continuous and Interrupted Broadband Noise by Normal-Hearing Listeners at Two Sensation Levels

In the first experiment stimuli were presented at 50 dB above participants' SRTs. It was observed, as with Phillips and colleagues who presented their stimuli at 40 dB SL (Phillips et al., 1994; Rappaport et al., 1994), that some normal-hearing participants report that the stimuli presentation level was uncomfortable, specifically in the adverse S/Ns (i.e., -15 and 20 dB). As many hearing-impaired listeners suffer from loudness recruitment, it was deemed that a 50 dB SL presentation level would be intolerable. Toward that end it was decided that a 30 dB SL presentation level would be acceptable for hearing-impaired listeners. Previous pilot work had suggested that this was an appropriate level.

To the best of the author's knowledge, there have been no reports of the effect of sensation level on word recognition performance in interrupted broadband noise while only one study has reported the effect of sensation level on word recognition performance in continuous broadband noise. Rupp et al (1977) studied the word recognition performance of 20 college students, for monosyllabic CID W-22 word list stimuli presented monaurally in continuous broadband noise. Two sensation levels (30 and 50 dB) and two S/Ns (0 and -10 dB) were employed. The findings revealed that performance was essentially equivalent at both sensation levels: Mean word recognition scores were at 58.8% and 18.5% at 30 dB SL versus 58 8% and 17 2% at 50 dB SL for S/Ns of 0 dB and -10 dB, respectively.

In the second experiment normal-hearing controls were retested at both sensation levels to assess the effect of presentation level on word recognition performance-intensity functions in both continuous and interrupted broadband noise. The purpose of the experiment was twofold: One, to compare the performance-intensity function differences at 30 and 50 dB SL among normal-hearing listeners, and two, to generate normative data at the 30 dB SL as a bench mark to compare hearing-impaired listeners' performance in subsequent experiments.

Method

Participants

Two groups of 12 young adult university undergraduate and graduate students served as participants. Group 1 consisted of 4 males and 8 females ($M = 24.9$ years, $SD = 3.1$) while Group 2 consisted of 5 and 7 males and females ($M = 24.8$ years, $SD = 3.0$), respectively. All participants presented with normal hearing sensitivity defined as having pure-tone thresholds at octave frequencies from 250 to 8000 Hz and SRTs of ≤ 25 dB HL (American National Standards Institute, 1989). The mean SRTs for Group 1 and 2 were 7.9 ($SD = 0.96$) and 6.7 ($SE = 1.1$), respectively. All participants presented with normal middle ear function (American Speech-Language-Hearing Association, 1990).

Stimuli

The test stimuli consisted of the same custom two channel stereo cassette tape recordings of NU-6 lists one to four described in the previous experiment. As well, the competing stimuli were the continuous or interrupted broadband noise.

Apparatus

The same double wall sound-treated audiometric suite (Industrial Acoustics Corporation) served as the test environment. The recorded stimuli were routed from a stereo cassette deck (AKAI Model GX-R66 or JVC Model

DD-V7) to a clinical audiometer (Grason Stadler GSI 10 Model 1710-9700) and presented to each participant through an insert earphone (Etymotic Research Model ER-3A). All noise reduction and filter systems on the stereo cassette deck were in the off position during testing.

Procedure

Testing was undertaken in one session of approximately one hour in duration. Participants were presented with the identical NU-6 stimuli. Group 1 received the stimuli at 30 dB SL re their respective SRTs while Group 2 at 50 dB SL re their respective SRTs. The speech stimuli were presented in quiet and in both broadband noises (continuous and interrupted) conditions with S/Ns of 10, 5, 0, -5, -10, -15, and -20. The presentation order of lists, noise condition, and S/N was determined with a Latin square design All test stimuli and noise competitors were presented monaurally to the right ear of each participant. Participants in both groups were presented with identical NU-6 stimuli.

Results

Participants' responses were scored as total whole word percent correct Mean word recognition performance in quiet was 92 3 % (*SE* = 1 1) and 94 7 % (*SE* = 1 1) for Group 1 and 2, respectively. Mean scores as a function of Auditory Condition (i.e. 30 dB SL vs. 50 dB SL) and S/N are shown in Figure 7. Participants in both groups displayed typical sigmoid performance-intensity functions in the continuous noise condition. As in the previous experiment, performance improved in the interrupted noise condition for both groups. Shallower performance-intensity functions were also evident in the interrupted noise.

Prior to subjecting the participants' proportional scores to inferential statistical analyses they were transformed to RAUs (Studebaker, 1985) With respect to mean word recognition performance in quiet, no statistically

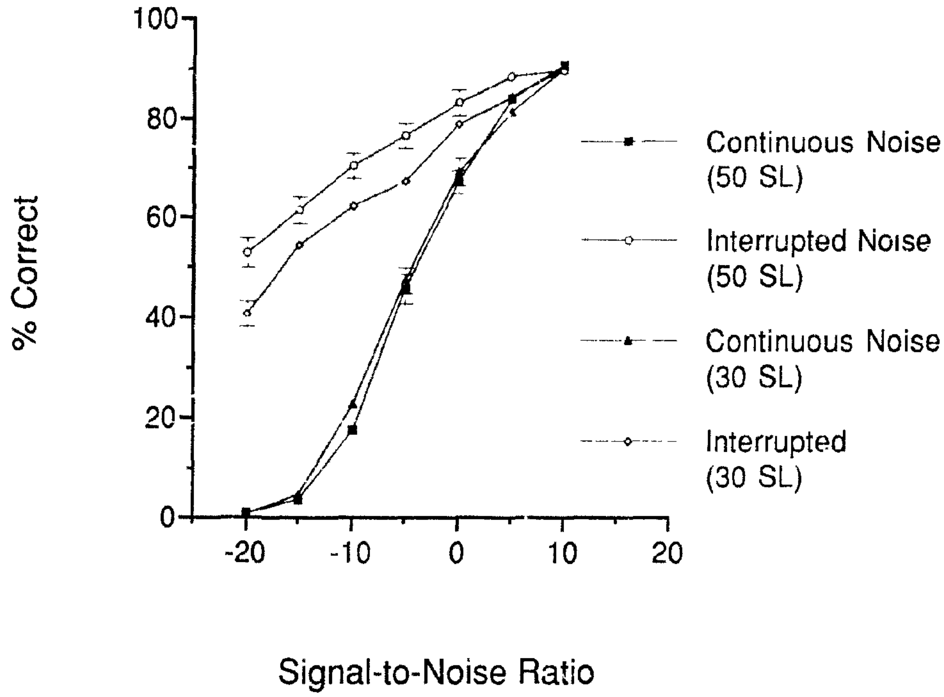

Figure 7: Mean percent correct word recognition score as function of Auditory Condition (i.e., 30 dB SL vs. 50 dB SL) and S/N (n = 12). Error bars represent plus/minus one standard error of the mean.

Table 3

Summary table for the mixed two-factor within-subjects ANOVA investigating word recognition performance in continuous broadband noise as a function of the Auditory Condition between-group factor (i.e., 30 dB vs. 50 dB SL) and the S/N within-group factor.

Source	Sum of Squares	*df*	Mean Square	*F*	*p*	$\hat{\omega}^2$
Auditory Condition	41.90	1	41.90	.67	423	.00
Error	1382.50	22	62.84			
S/N	255536.86	6	42589.48	639.71	<.0001*[a]	.92
Auditory Condition X S/N	307.53	6	51.26	.77	.595[b]	.00
Error	8788.04	132	66.58			

Note. *p* values following a Geisser-Greenhouse and Huynh-Feldt correction are [a].0001, .0001; and [b].569, .595 respectively.

* considered significant at $p < .05$.

Table 4

Summary table for the mixed two-factor within-subjects ANOVA investigating word recognition performance in continuous broadband noise as a function of the Auditory Condition between-group factor (i.e., 30 dB vs. 50 dB SL) and the S/N within-group factor.

Source	Sum of Squares	*df*	Mean Square	*F*	*p*	$\hat{\omega}^2$
Auditory Condition	1882.03	1	1882.03	12.41	.0019	.19
Error	3337.30	22	151.70			
S/N	39121.44	6	6520.24	125.35	<.0001*[a]	.69
Auditory Condition X S/N	477.96	6	79.66	1.53	.173[b]	.0094
Error	6865.98	132	52.02			

Note. *p* values following a Geisser-Greenhouse and Huynh-Feldt correction are [a].0001, .0001; and [b].191, .173 (probability was not corrected as the epsilon value was greater than one) respectively.

* considered significant at $p < .05$.

significant difference was found between Group 1 and 2, $t(22) = -1.55$, $p = .136$. In other words, there was no effect of SL presentation on word recognition performance in quiet. To investigate mean word recognition performance differences as a function of Auditory Condition (i.e., 30 dB SL vs 50 dB SL) and S/N for both continuous and interrupted broadband noise conditions, separate mixed two-factor ANOVAs were undertaken. The results of each ANOVA are presented in Tables 3 and 4, respectively. A significant main effect was observed for S/N in both continuous and interrupted broadband noise conditions ($p < .05$). Again, performance increased with increases in S/N regardless of noise condition. A significant main effect for Auditory Condition was only observed in the interrupted noise condition ($p < .05$). That is, performance was higher for the 50 versus 30 SL for the interrupted noise condition only. No interactions of main effects were significant in either noise condition ($p > .05$). Relative treatment magnitudes are indexed in both Tables by partial omega squared ($\hat{\omega}^2$, Keppel, 1991; Keren & Lewis, 1979)

Discussion

The findings of this experiment were threefold: First, to no surprise, there was no effect of SL presentation on word recognition performance in quiet. It has been established that word recognition maximum performance typically peaks at 20 to 30 dB SL re the listener's SRT (Beattie, Edgerton, & Svihovec, 1977; Rintelmann et al., 1975; Tillman & Carhart, 1966; Tillman & Olsen, 1973; Wilson et al., 1975). One would not expect any performance-intensity function "rollover" in normal-hearing listeners with the change in presentation level employed in this experiment (e.g., Bess, Josey, & Humes, 1979; Dirks, Kamm, Bower, & Betsworth, 1977; Jerger & Jerger, 1971). In other words, maximum word recognition performance should be established at the 30 SL presentation level and there should not be any deterioration with increasing speech intensity. Consequently, one would not expect to see any performance differences between the two groups in quiet Second, as in the first experiment and expected, performance increased with increases in S/N regardless of noise condition Finally, performance was superior for the 50 versus 30 SL presentation for the interrupted noise condition only This latter finding deserves some comment

The finding of no difference between the two groups' performance at different SLs in the continuous broadband noise was consistent with those of Rupp et al. (1977). These findings may be explained with what is known about the ipsilateral masking function Regardless of any masker/maskee combination, it is well established that once a masker has caused a threshold shift, further increases in the masker level result in a linear equal dB shift in the maskee threshold (e g , see Konkle & Berry, 1983) Hawkins and Stevens (1950) reported that the thresholds of both detectability and intelligibility for speech in noise are linear for SLs of noise from 20 to 90 dB The fact that the this linear relationship exists, and that relative levels of masker and speech were maintained when shifting SL (i e , the S/Ns were the same in both SL presentations), suggests that the performance intensity function shapes should be preserved. In other words, the recognition of speech stimuli in noise is governed by audibility of the speech stimuli If the relationship of the speech stimuli and competing noise remains the same at suprathreshold levels one would expect the audibility of the speech stimuli to remain the same as well In this case the performance-intensity function should remain the same One would anticipate this to be true for presentation levels where maximum word recognition performance in quiet has been established (i e , at 20 to 30 dB SL and above re the listener's SRT).

The observation of group differences in the interrupted noise condition may be explained in terms of the forward and backward masking effects as a function of masker level. As outlined earlier it is recognized that the silent intervals between bursts of noise are not immune to the influence of noise bounding them. The gaps are subject to spill-over from the noise as a consequence of forward and backward masking. It has been established that the extent of forward masking (Festen & Plomp, 1981, 1983; Jestead Bacon & Lehman, 1982; Plomp, 1964; Smiarowski & Carhart, 1975, Widen & Viemeister, 1979) and backward masking (Elliot, 1962a; Fastl, 1976, Festen & Plomp, 1981 1983; Pickett, 1959) are independent of the masker level in normal-hearing listeners The period of time that a noise masks a preceding (in backward masking) or following signal (in forward masking) is approximately 25 to 50 ms and 150 to 200 ms, respectively, independent of the masker level This being the case, it can been seen that the slopes of backward and forward masking become steeper at increasing masker levels[5]. The influence of these masking slopes is different for each temporal masker With forward masking the time of recovery from effective masking (or release from masking) is always faster for higher masking than lower masking levels. With backward masking the duration of effective masking is always shorter for higher masking than lower masking levels. It stands to reason that superior performance should be observed in interrupted noise at higher sensation levels because the duration of effective masking effects are less

Hypothetical masking functions illustrating these concepts are shown in Figure 8. The gap between the two noise bursts illustrated in the figure is larger than that employed with the listeners of this study for the sake of simplicity in depicting the complete masking functions. The target speech signals are depicted as being presented at 50 and 30 SL at a -10 dB S/N (i.e., the masker

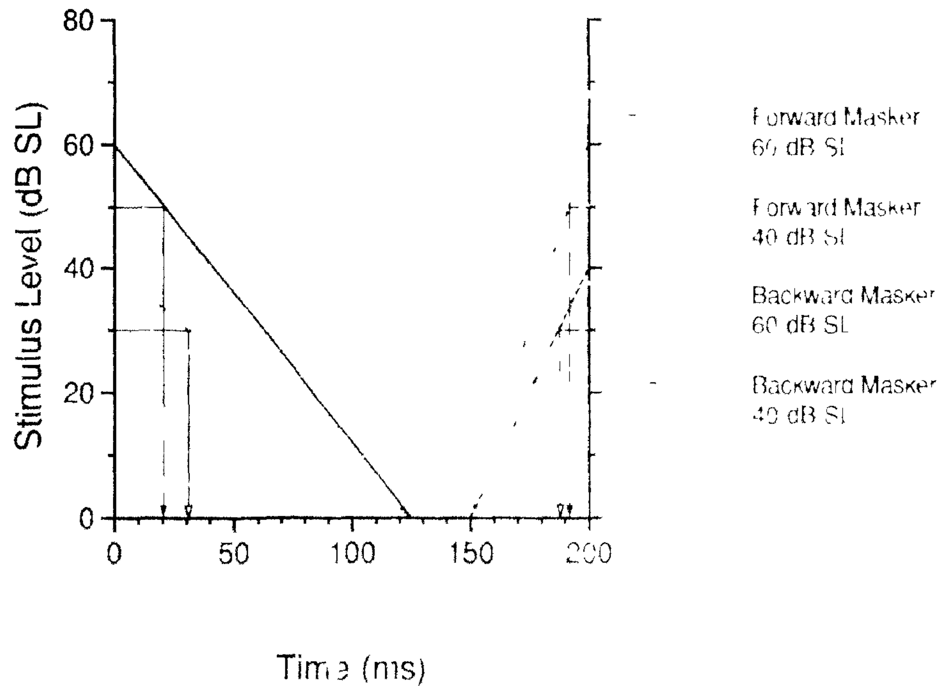

Figure 8: Hypothetical masking functions for 60 and 40 dB SL maskers The target speech signals are presented at 50 and 30 SL (i e , -10 dB S/N).The times, when a release from masking after the offset of the forward masker and the onset of backward masking effects occur, are noted with closed and solid arrowheads for the 60 and 40 dB maskers, respectively.

levels are 60 and 40 dB for the 50 and 30 dB speech signals, respectively). The duration of the forward maskers' decay is 125 ms The duration of the masking effects preceding the backward maskers is 50 ms The time at which masking effects are released (in the case of forward masking) or come into effect (in the case of backward masking) are noted with closed and solid arrowheads for the 60 and 40 dB maskers, respectively. The times after the offset of the forward masker when release from masking occurs, in this example, are approximately 20 and 31 ms for the 60 and 40 dB masker, respectively. The times when backward masking effects occur, in this example, are approximately 8 and 12 ms for the 60 and 40 dB SL masker, respectively. The durations of the gaps where masking is not effective are approximately 172 and 157 ms for the 60 and 40 dB masker, respectively. The slopes of the masking functions influence both the depth and width of the silent gap Since the silent gaps between noise bursts are of longer duration and of greater depth, at the high sensation level, a greater release from masking should occur.

The findings, that the listeners who were presented stimuli at 50 dB SL performed significantly higher than those listeners who were presented stimuli at 30 dB SL in the interrupted noise condition, are consistent with the phenomenon described above. One has to acknowledge that the hypothetical masking functions illustrated above represent an oversimplification as signals positioned in the silent gaps between noise bursts are influenced by both forward and backward masking in a manner that is greater than the simple summation of the two (Elliot, 1969; Fastl, 1976, 1977, 1979; Patterson, 1971, Pollack, 1964; Robinson & Pollack, 1973; Wilson & Carhart, 1971). It has also been confirmed with another time varying masker (i.e., interfering voice) that the release from masking is limited by forward masking and governed by its level (Festen, 1993; Festen & Plomp, 1987).

Chapter 3

Word Recognition Performance in Continuous and Interrupted Broadband Noise by Young Normal Hearing, Older Normal Hearing, and Presbycusic Listeners

As outlined earlier, numerous studies have revealed performance detriments on tasks exploring auditory temporal phenomena among presbycusic listeners. There was, however, little consensus on the nature of the temporal resolution deficit among presbycusic listeners. It was suggested that performance impairments observed with presbycusic listeners on temporal resolution tasks may be a consequence of peripheral hearing loss and or other independent age-related factors. It was also proposed that disorders in temporal processing may be in part responsible for the decline in speech understanding that accompanies senescence.

The D. P. Phillips et al. (1994) interrupted noise paradigm was offered as a tool to reveal not only deficits in temporal processing associated with the peripheral hearing impairment but also any deficit that may be a consequence of central factors independent of the peripheral pathology. As such, it appears that the paradigm may reveal insights into the existence and severity of a temporal resolution deficit with listeners suffering from presbycusis. In the third experiment of this thesis, it was proposed that performance-intensity functions for word recognition in continuous and interrupted broadband noise as a function of S/N be examined among young normal-hearing adults, cognitively-intact older normal-hearing adults, and cognitively intact, age-matched presbycusic adults. It was speculated that performance differences revealed by this quantitative speech-in-noise paradigm would reveal the contribution of any peripheral and central temporal resolution deficits towards word recognition performance.

In the present study, it was hypothesized that cognitively-intact hearing-impaired presbycusic listeners should demonstrate a detriment in performance relative to young normal-hearing listeners in both continuous and broadband noise as a consequence of their hearing impairment. The disadvantage in continuous noise should be a repercussion of reduced audibility and impoverished frequency resolution in the high frequencies. The disadvantage in interrupted noise should be similar to that of the noise-induced hearing-impaired listeners employed by D.P. Phillips et al. (1994). That is, one should observe a reduced ability to temporally resolve auditory information between the gaps of noise as a consequence of inferior temporal resolution resulting from restricted low frequency channel capacity. Any concomitant decline in central auditory processing may contribute, as well, to the predicted impaired performance with the presbycusic listeners. The hearing-impaired presbycusic listeners should also demonstrate a similar detriment in performance, in both continuous and broadband noise relative, to "normal-hearing" cognitively-intact aged matched listeners. Any observed differences in both noise conditions between the normal-hearing and hearing-impaired older listeners should reveal the effects of the peripheral hearing loss alone. A comparison of the young normal-hearing listeners' and the older normal-hearing listeners' performance should reveal any contribution of aging. A comparison of the young normal-hearing and older hearing-impaired listeners should reveal the combined effect of peripheral hearing loss and aging and possibly the interaction of the two effects. The purpose of the third experiment was to investigate this speculation.

Method

Participants

Three groups of 12 adults served as participants in the third experiment. Group 1 consisted of the same 12 young adult university undergraduate and graduate students that served as Group 1 in the previous experiment. That is, the 4 males and 8 females (*M* = 24.9 years, *SD* = 3.1). As detailed previously, they presented with normal-hearing sensitivity defined as having pure-tone thresholds at frequencies of 250, 500, 1000, 2000, 3000, 4000, and 8000 Hz of 25 dB HL (American National Standards Institute, 1989) or better. The mean SRT for Group 1 was 7.9 (*SE* = 0.96).

Groups 2 and 3 consisted of 12 age-matched older participants between the ages of 55 and 70 years. Group 2 consisted of seven males and five females with a mean age of 61.0 years (*SD* = 4.5). Group 3 consisted of seven females and five males with a mean age of 62.8 years (*SD* = 4.0). There was no statistically significant difference between these mean ages, $t(22) = -1.13$, $p = .269$. English was the first language of both groups. The Mini-Mental State (Folsten, Folsten, & McHugh, 1975) was employed to assess the cognitive mental status of these older participants. The test consists of two parts: "the first of which requires vocal responses only and covers orientation, memory, and attention.... The second parts tests ability to name follow verbal and written commands, write a sentence spontaneously, and copy a complex polygon..." (Folsten et al., p. 190). Participants in both groups scored 24 or higher out of a possible total score of 30[6]. As well, participants of both groups presented with a vocabulary age equivalent score of 12-1 years or more as assessed by the Peabody Picture Vocabulary Test-Revised (Form L, Dunn & Dunn, 1981). It is felt that the NU-6 materials are appropriate for individuals with a vocabulary ages of 11 and one-half years and older (Sanderson-Leepa & Rintelmann, 1976). Finally, all participants from these two groups were ambulatory and in good health.

Group 2 participants presented with normal hearing as defined as having pure-tone thresholds of ≤ 25 dB HL (American National Standards Institute) at frequencies of 250, 500, 1000, 2000, 3000, and 4000 Hz. Their mean SRT was 15.0 (*SE* = 1.5). Group 3 consisted of participants with high-frequency sloping sensorineural hearing losses. These individuals' test ear had normal-hearing pure-tone thresholds of ≤ 25 dB HL in octave steps from 250 to 1000 Hz and thresholds of 35, 60, and 60 dB HL (American National Standards Institute) or better at 2000, 3000, and 4000 Hz, respectively. Air-bone gaps were less than 15 dB. Their mean SRT was 20.8 (*SE* = 0.53). For the most part, all participants in Group 3 had symmetrical hearing losses. All but two participants had interaural four-frequency pure-tone averages (PTAs) within 15 dB HL. PTAs were arithmetic means calculated from audiometric thresholds at 500, 1000, 2000, and 4000 Hz. All of these older participants presented with normal middle ear function (American Speech-Language-Hearing Association, 1990). Both groups of individuals had a negative history of neurological disorders, otological disease, vertigo or persistent tinnitus, ototoxic drug use, chronic otitis media, middle ear dysfunction, head trauma and/or surgery, speech and language disorders, and significant occupational and recreational noise exposure. The presumed etiology of hearing impairment for Group 3 was presbycusis. The hearing-impaired older participants were solicited from the files of the Nova Scotia Hearing and Speech Clinic at the Halifax Infirmary Hospital, Halifax, NS. Prospective participants were contacted by telephone and requested to partake in the study. The participants from Group 2 were volunteers who responded to advertisements soliciting participation in the study.

Pure-tone audiograms of the 12 participants in each of the young normal-hearing (YNH) Group 1, older normal-hearing (ONH) Group 2, and older

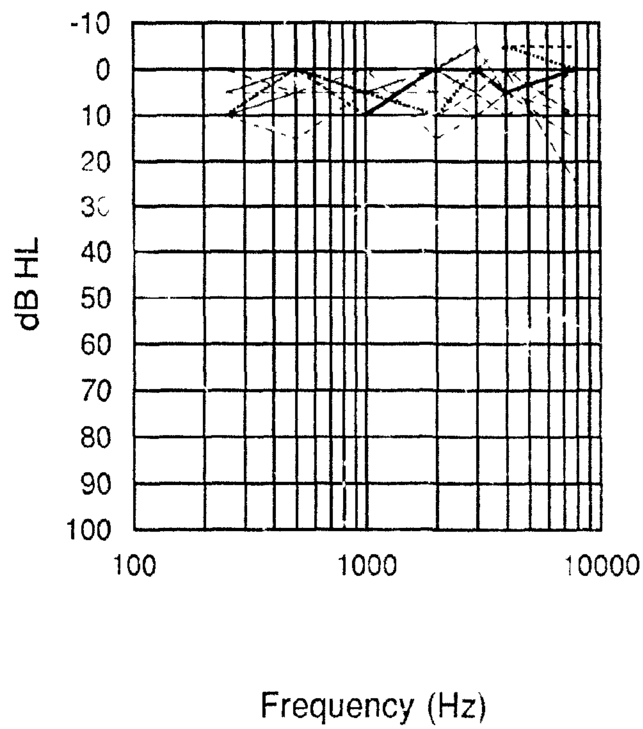

Figure 9 Audiometric pure-tone thresholds (dB HL) for each of the 12 young normal-hearing participants from Group 1.

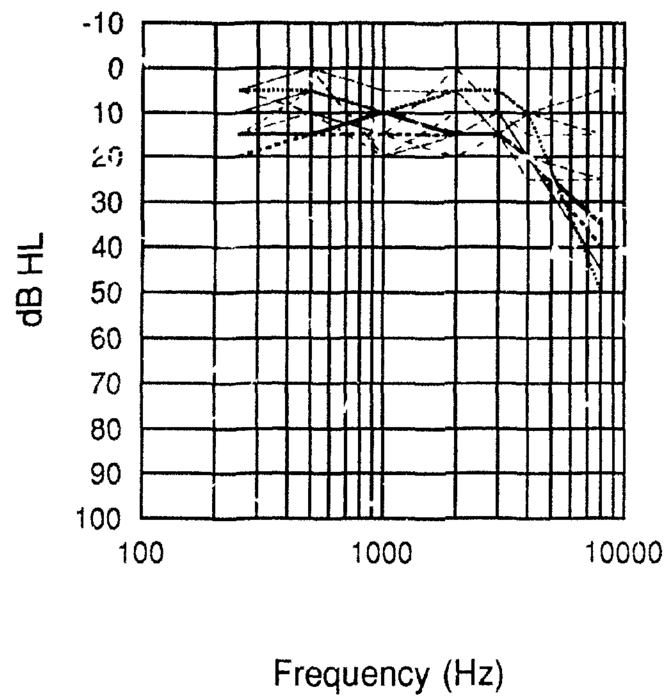

Figure 10: Audiometric pure-tone thresholds (dB HL) for each of the 12 older normal-hearing participants from Group 2.

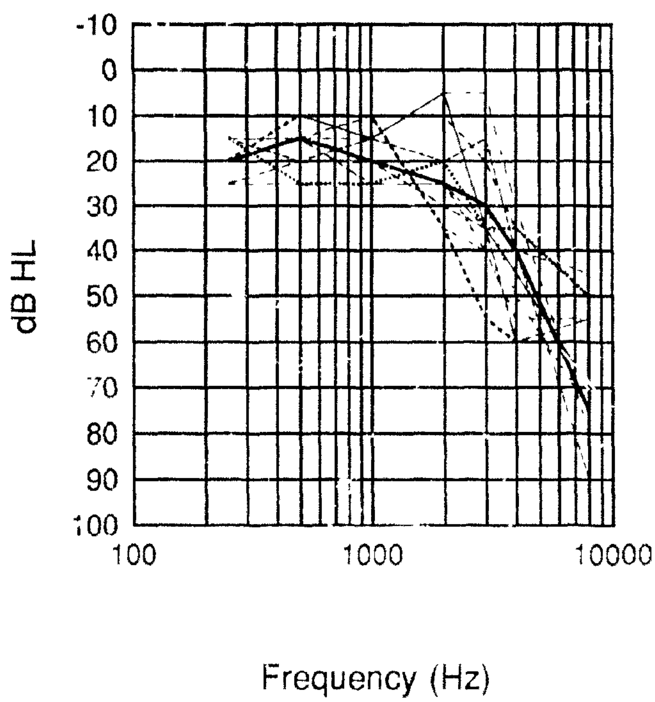

Figure 11: Audiometric pure-tone thresholds (dB HL) for each of the 12 older hearing-impaired participants from Group 3.

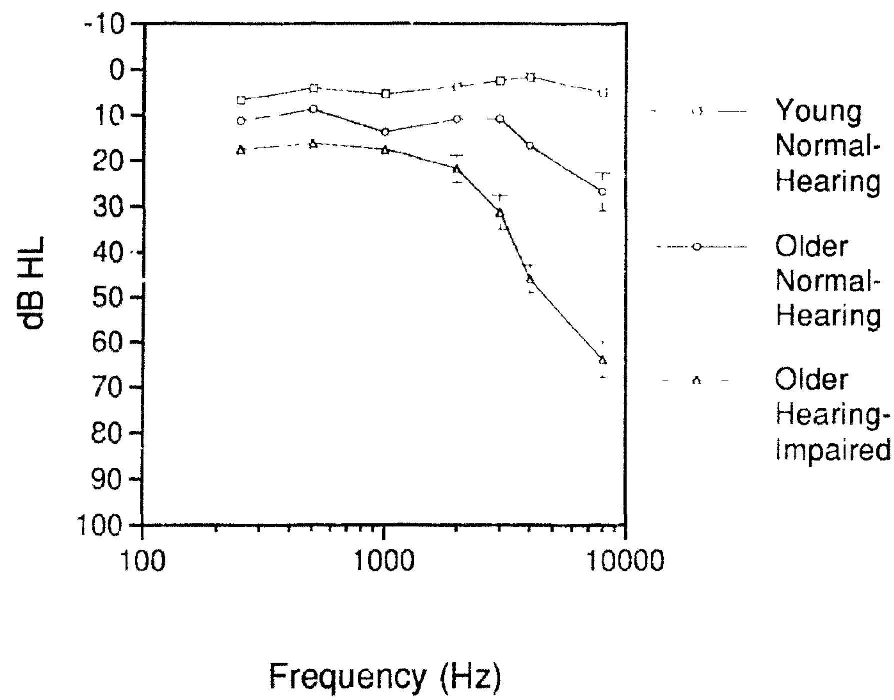

Figure 12: Mean audiometric pure-tone thresholds (dB HL) for the Young Normal-Hearing Group 1, Older Normal-Hearing Group 2, and Older Hearing-Impaired Group 3. Error bars represent plus/minus one standard error of the mean.

hearing-impaired (OHI) Group 3 are presented in Figures 9, 10 and 11, respectively. Figure 12 displays the mean pure-tone audiograms from the three groups. A single-factor between-subjects ANOVA was undertaken to investigate the differences between groups with respect to hearing sensitivity. Hearing sensitivity was operationally defined as a four-frequency PTA for 500, 1000, 2000, and 4000 Hz. The results of that ANOVA are presented in Table 5. A statistically significant Group effect was observed ($p < .0001$). A Tukey (1953) F-test post hoc pair-wise comparison confirmed the observation, evident in Figure 12, that all groups had significantly different hearing sensitivity relative to the others ($p < .05$). The results are found in Table 6. Specifically, the YNH group had the best hearing sensitivity, as indexed by a four-frequency PTA, followed by the ONH and OHI groups, respectively.

Stimuli

The same custom two channel stereo cassette tape recordings of NU-6 lists one to four described in the previous experiments served as the test stimuli. The competing stimuli were again the continuous and interrupted broadband noise.

Apparatus

The double wall sound-treated audiometric suite (Industrial Acoustics Corporation) described previously served as the test environment. The recorded stimuli were routed from a stereo cassette deck (JVC Model DD-V7) to a clinical audiometer (Grason Stadler GSI 10 Model 1710-9700) and presented to each participant through an insert earphone (Etymotic Research Model ER-3A). All noise reduction and filter systems on the stereo cassette deck were in the off position during testing.

Table 5

Summary table for the single-factor between-subjects ANOVA investigating four-frequency pure-tone average (dB HL) as a function of Group (i.e., young normal-hearing vs. older normal-hearing vs. older hearing-impaired listeners).

Source	Sum of Squares	*df*	Mean Square	*F*	*p*	$\hat{\omega}^2$
Group	2822.66	2	1411.33	78.80	<.0001*	.81
Error	591.02	33	17.91			

Note. Pure-tone averages were calculated from audiometric thresholds at 500, 1000, 2000, and 4000 Hz.

* considered significant at $p < .05$

Table 6

Tukey pair-wise comparisons of four-frequency pure-tone averages (dB HL) as a function of Group.

M	Group	YNH	ONH	OHI
3.8	YNH			
12.5	ONH	*		
25.3	OHI	*	*	

Note. Pure-tone averages were calculated from audiometric thresholds at 500, 1000, 2000, and 4000 Hz. YNH = young normal-hearing; ONH = older normal hearing; OHI = older hearing-impaired

* denotes pairs of means significantly different at $p < .05$ (two tailed)

Procedure

Testing was undertaken in one session of approximately one hour in duration. All groups of participants were presented with the identical NU-6 stimuli at 30 dB SL re: their respective SRTs. The speech stimuli were presented in quiet and in both broadband noises (continuous and interrupted) conditions with S/Ns of 10, 5, 0, -5, -10, -15, and -20. The presentation order of lists, noise condition, and S/N was determined with a Latin square design. All test stimuli and noise competitors were presented monaurally to the right ear of each participant.

Results

Participants' responses were scored as total whole word percent correct. Mean word recognition performance in quiet was 92.3 % (*SE* = 1.1), 91.3 (*SE* = 1.3), and 86.5 % (*SE* = 1.1) for the YNH, ONH, and OHI groups, respectively. Mean scores as a function of Group and S/N are shown in Figures 13 and 14 for continuous and interrupted broadband noise, respectively. Participants in all groups displayed typical sigmoid performance-intensity functions in the continuous noise condition. As in the previous experiment, performance improved in the interrupted noise condition for all groups Shallower performance-intensity functions were also evident in the interrupted noise condition.

Prior to subjecting the participants' proportional scores to inferential statistical analyses, they were transformed to RAUs (Studebaker, 1985). With respect to mean word recognition performance in quiet as a function of Group and S/N a single-factor between-subjects ANOVA was undertaken. The results are presented in Table 7. A statistically significant Group effect was found ($p < .05$). In order to ascertain which group mean word recognition performances were different, a Tukey (1953) *F*-test post hoc pair-wise comparison was

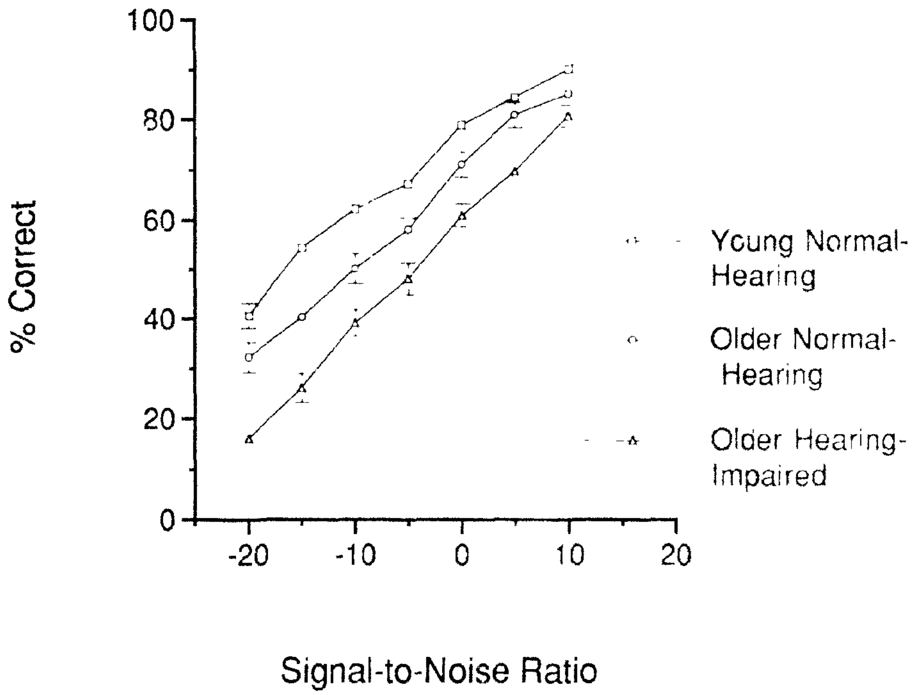

Figure 13: Mean percent correct word recognition score in continuous broadband noise as function of Group and S/N (n = 12). Error bars represent plus/minus one standard error of the mean.

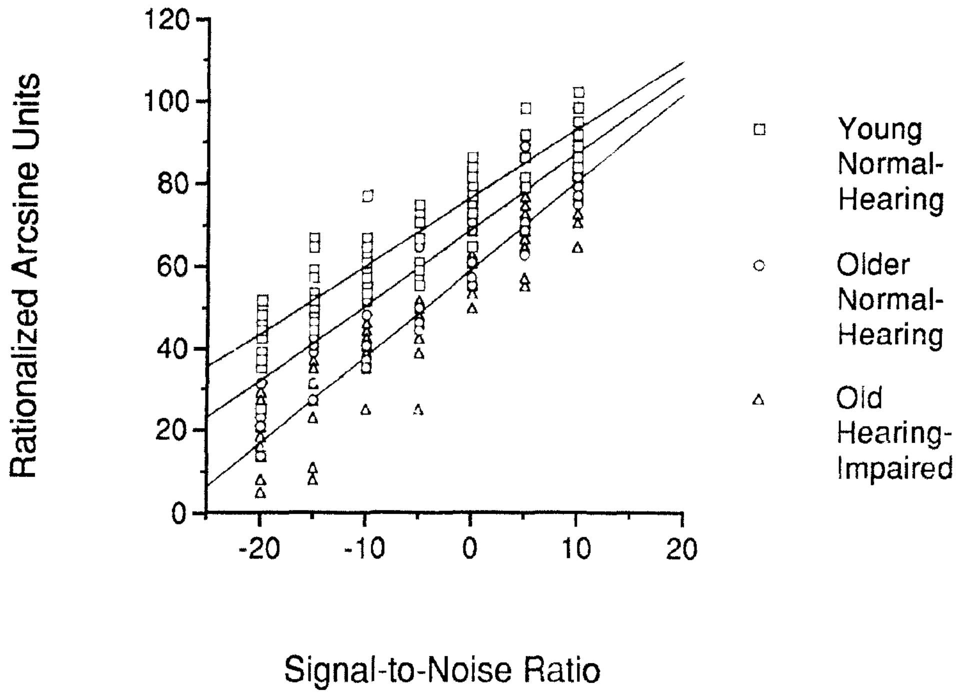

Figure 14: Mean percent correct word recognition score in interrupted broadband noise as function of Group and S/N (n = 12). Error bars represent plus/minus one standard error of the mean.

Table 7

Summary table for the single-factor between-subjects ANOVA investigating word recognition performance in quiet as a function of Group (i.e., young normal-hearing vs. older normal-hearing vs. older hearing-impaired listeners).

Source	Sum of Squares	*df*	Mean Square	*F*	*p*	ω^2
Group	537.91	2	268.95	6.84	.0033*	.098
Error	1298.21	33	39.34			

Note. * considered significant at $p < .05$

Table 8

Tukey pair-wise comparisons of transformed means of word recognition percent correct scores in quiet as a function of Group.

M	Group	OHI	ONH	YNH
87.3	OHI			
94.6	ONH	*		
96.2	YNH	*		

Note. YNH = young normal-hearing; ONH = older normal-hearing; OHI = older hearing-impaired.

* denotes pairs of means significantly different at $p < .05$ (two-tailed).

performed. These results are found in Table 8. Specifically, the OHI group mean word recognition performance was significantly different from both the YNH and ONH groups ($p < .05$).

To investigate mean word recognition performance differences as a function of Group and S/N for both continuous and interrupted broadband noise conditions, separate mixed two-factor ANOVAs were undertaken. The results of the ANOVA investigating performance in continuous noise are presented in Table 9. Significant main effects were observed for both Group and S/N ($p < .05$). A nonsignificant Group by S/N interaction was evident. Not surprisingly, performance increased with increases in S/N for all groups. A Tukey (1953) *F*-test post hoc pair-wise comparison was employed to investigate group mean word recognition performance collapsed across S/N. The results of this analysis are found in Table 10. It was found that all pair-wise comparisons were statistically significant ($p < .05$). That is, all groups performed differently, with superior performance being displayed by the YNH group followed by the ONH and OHI groups, respectively.

The results of the ANOVA investigating performance in interrupted noise are presented in Table 11. Significant main effects were found for Group and S/N, as well as a significant Group by S/N interaction ($p < .05$). In order to investigate group mean word recognition performance collapsed across S/N a Tukey (1953) *F*-test post hoc pair-wise comparison was performed. The results of this analysis are found in Table 12. As evident in Table 12, all pair-wise comparisons were statistically significant ($p < .05$). Again, all groups performed differently with superior performance being displayed by the YNH group followed by the ONH and OHI groups, respectively.

Table 9

Summary table for the mixed two-factor within-subjects ANOVA investigating word recognition performance in continuous broadband noise as a function of Group (i.e., young normal-hearing vs. older normal-hearing vs. older hearing-impaired) and S/N.

Source	Sum of Squares	*df*	Mean Square	*F*	*p*	$\hat{\omega}^2$
Group	3394.57	2	1697.28	14.31	<.0001*	.20
Error	3895.32	33	118.04			
S/N	360359.41	6	60059.90	1072.16	<.0001*[a]	.89
Group X S/N	707.51	12	58.96	1.05	.403[b]	.00083
Error	11091.54	198	56.02			

Note. *p* values following a Geisser-Greenhouse and Huynh-Feldt correction are [a].0001, .0001; and [b].401, .402 respectively.

* considered significant at $p < .05$.

Table 10

Tukey pair-wise comparisons of transformed means of word recognition percent correct scores in continuous broadband noise collapsed across S/N as a function of Group.

M	Group	OHI	ONH	YNH
36.5	OHI			
38.1	ONH	*		
42.5	YNH	*	*	

Note. YNH = young normal-hearing; ONH = older normal-hearing; OHI = older hearing-impaired.

* denotes pairs of means significantly different at $p < .05$ (two-tailed).

Table 11

Summary table for the mixed two-factor within-subjects ANOVA investigating word recognition performance in interrupted broadband noise as a function of Group (i.e., young normal-hearing vs. older normal-hearing vs. older hearing-impaired) and S/N.

Source	Sum of Squares	*df*	Mean Square	*F*	*p*	$\hat{\omega}^2$
Group	16454.81	2	8227.41	48.00	<.0001*	.47
Error	5655.76	33	171.39			
S/N	88845.45	6	14807.57	301.49	<.0001*[a]	.70
Group X S/N	1230.67	12	102.56	2.09	.0192[b]	.017
Error	9724.60	198	49.11			

Note. *p* values following a Geisser-Greenhouse and Huynh-Feldt correction are [a].0001, .0001; and [b]..0317, .0201 respectively.

* considered significant at $p < .05$.

Table 12

Tukey pair-wise comparisons of transformed means of word recognition percent correct scores in interrupted broadband noise collapsed across S/N as a function of Group.

M	Group	OHI	ONH	YNH
48.8	OHI			
59.9	ONH	*		
68.5	YNH	*	*	

Note. YNH = young normal-hearing, ONH = older normal-hearing, OHI = older hearing-impaired.

* denotes pairs of means significantly different at $p <$ .05 (two-tailed)

To further investigate the significant Group by S/N interaction found with the ANOVA examining word recognition performance in interrupted noise, the relationship between group word recognition performance and S/N was examined with correlation and regression analyses. A statistically significant positive correlation was found between word recognition scores and S/N for all groups ($p < .0001$). Pearson product-moment correlation coefficients (*r*) and their 95% confidence intervals (lower and upper) were .93 (.89 and .95), .91 (.86 and .94), and .93 (.89 and .95) for the YNH, ONH, and OHI groups, respectively. Simple linear regression analyses revealed a statistically significant relation between S/N and word recognition performance scores for all groups. That is, knowledge of S/N will enhance the prediction of word recognition scores for all groups. The results of these analyses are presented in Tables 13 and 14. Violations of assumptions of linearity, normality, and homoscedasticity were not revealed following examinations of scatterplots of residuals against predicted values, residuals against individual independent values, and individual independent values against predicted values. The differences among the slopes or regression coefficients (*B*) were also tested (i.e., are the population slopes or regression coefficients different from zero). The analyses from separate *t*-tests are found in Table 15. For all groups, the null hypothesis was rejected. That is, the separate slopes were different from zero, and therefore knowledge of S/N enhances the prediction of word recognition score. The bivariate scatter plot and respective linear regression lines for word recognition performance (in RAUs) as a function of experimental group data are presented in Figure 15.

Further analyses was undertaken to investigate the significance of the differences between independent slopes or regression coefficients (Cohen & Cohen, 1983). The results of unpaired two-tailed *t*-tests evaluating pair-wise

Table 13

Summary table for the ANOVA investigating the linear relationship between percent correct word recognition performance in broadband interrupted noise as a function of Group and S/N.

Source	Sum of Squares	*df*	Mean Square	*F*	*p*
Young Normal-Hearing					
Regression	23009.46	1	23009.46	497.46	<.0001*
Residual	3792.78	82	46.25		
Older Normal-Hearing					
Regression	28590.12	1	28590.12	385.83	<.0001*
Residual	6076.22	82	74.10		
Older Hearing-Impaired					
Regression	37950.34	1	37950.34	515.43	<.0001*
Residual	6037.51	82	73.63		

Note. * considered significant at $p < .05$.

Table 14

Regression line equations for predicting word recognition performance (in RAUs) in broadband interrupted noise from S/N as a function of Group.

Young Normal-Hearing

Predicted word recognition score $= \frac{1.66 \text{ RAU}}{\text{S/N}} * \text{S/N} + 76.78 \text{ RAU}$

Older Normal-Hearing

Predicted word recognition score $= \frac{1.84 \text{ RAU}}{\text{S/N}} * \text{S/N} + 69.08 \text{ RAU}$

Older Hearing-Impaired

Predicted word recognition score $= \frac{2.13 \text{ RAU}}{\text{S/N}} * \text{S/N} + 59.39 \text{ RAU}$

Note. In predicting y scores from x scores, the equation for the straight line used in prediction is $\hat{y} = Bx + A$, where $\hat{y}$ is the predicted score, B is the slope of the line, and A is the Y intercept.

Table 15

Summary of two-tailed t-tests examining the significance of the independent regression coefficients (B) as a function of Group.

	B	*SE* of *B*	Standardized *B*	*t*	*p*
Young Normal-Hearing					
	1.66	0.074	0.93	22 30	<.0001*
Older Normal-Hearing					
	1.84	0.094	0 91	19 64	< 0001*
Older Hearing-Impaired					
	2.13	0.094	0.93	22 70	< 0001*

Note. * considered significant at $p < .05$

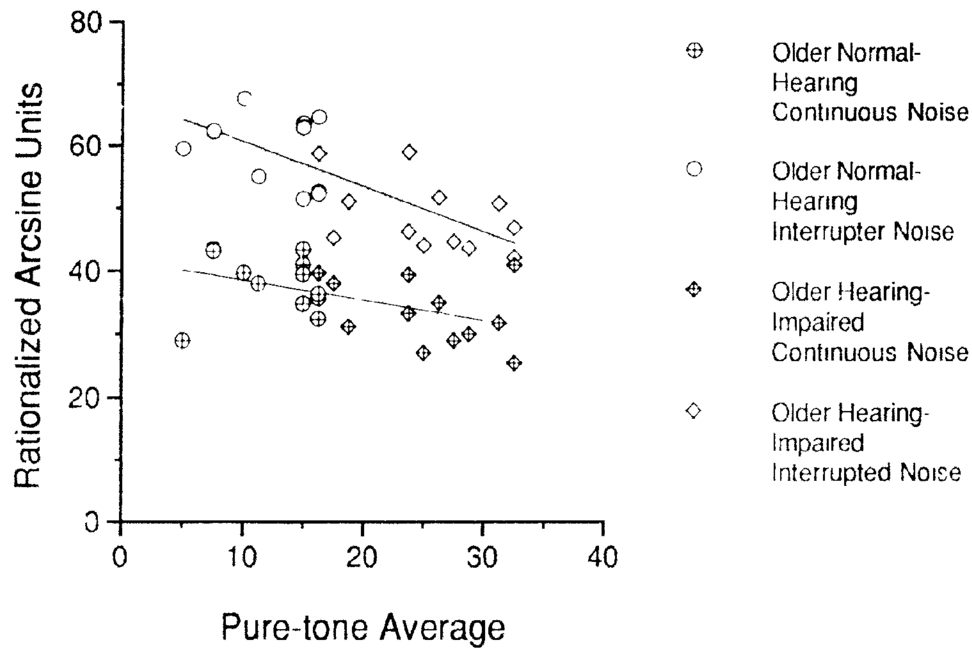

Figure 15: Bivariate scatterplots and regression lines for word recognition performance (in RAUs) in interrupted noise as a function of Group and S/N.

Table 16

Summary of two-tailed t-tests examining the significance of differences between pair-wise comparisons of independent regression coefficients.

Difference between *B*'s	*df*	*t*	*p*
Young Normal-Hearing vs. Older Normal-Hearing			
0.19	164	1.78	< 05*
Young Normal-Hearing vs. Older Hearing-Impaired			
0.47	164	4 41	< 01*
Older Normal-Hearing vs. Older Hearing-Impaired			
0.28	164	2 37	< 01*

Note. * considered significant at $p <$ 05 comparisons of the independent *B*'s are found in Table 16. Essentially all pair-wise comparisons were statistically different. These results suggest that group performance is differentially affected by S/N. In other words, as S/N becomes more favorable word recognition improves at different rates or, conversely, as S/N becomes more adverse word recognition performance decreases at different rates. Specifically, the degree of change in word recognition performance as a function of S/N is greatest in the OHI group followed by the ONH group, and finally by the YNH group.

Finally, further investigation of the performance of the two older groups of listeners was undertaken. ANOVAs by their design explore differences between two or more treatment groups. In the previous analyses, groups were categorized in clinical terms as being either normal-hearing or hearing-impaired. What is often overlooked with this categorical distinction and with ANOVAs is the relationship among variables. It was of interest to explore word recognition performance as a function of hearing sensitivity. Correlation and regression analyses were carried to examine this relationship. By exploring the older groups of listeners it was possible to hold the age variable constant.

Transformed word recognition scores from both the ONH and OHI groups were collapsed across S/N for both continuous and interrupted broadband noise as a function of four-frequency PTA and subjected to correlation and linear regression analyses. A statistically significant negative correlation was found between PTA and word recognition scores for both noise conditions. Pearson product-moment correlation coefficients (*r*) and their 95% confidence intervals (lower and upper) were -.48 (-.74 and -.10) and -.74 (-.88 and -.48) for the continuous and interrupted noise, respectively. Linear regression analyses revealed a statistically significant relation between PTA and word recognition performance scores in both noise conditions. That is, as PTA increases word

Table 17

Summary table for the ANOVA investigating the linear relationship between percent correct word recognition performance in broadband continuous and interrupted noise as a function of four-frequency pure-tone average (dB HL) for the older participants.

Source	Sum of Squares	*df*	Mean Square	*F*	*p*
Continuous Broadband Noise					
Regression	152.51	1	152.51	6 65	017*
Residual	504 63	22	22.94		
Interrupted Broadband Noise					
Regression	776.90	1	776.90	26 32	<.0001*
Residual	649 42	22	29 52		

Note. Pure-tone average was calculated from audiometric thresholds at 500, 1000, 2000, and 4000 Hz.

* considered significant at $p < .05$.

Table 18

Regression line equations for predicting word recognition performance (in RAUs) in broadband continuous and interrupted noise as a function of four-frequency PTA (dB HL) for the older participants.

Continuous Broadband Noise

Predicted word recognition score = $\frac{-.32 \text{ RAU}}{\text{S/N}}$ *PTA + 41.80 RAU

Interrupted Broadband Noise

Predicted word recognition score = $\frac{-.72 \text{ RAU}}{\text{S/N}}$ *PTA + 67.86 RAU

Note: In predicting y scores from x scores, the equation for the straight line used in prediction is $\hat{y} = Bx + A$, where $\hat{y}$ is the predicted score, *B* is the slope of the line, and A is the Y intercept.

Table 19

Summary of two-tailed t-tests examining the significance of the independent regression coefficients (B) for both noise condition

B	*SE* of *B*	Standardized *B*	*t*	*p*
Continuous Broadband Noise				
-.32	0.12	-.48	-2.56	.017*
Interrupted Broadband Noise				
-.72	0.14	-.74	-5.13	<.0001*

Note. * considered significant at $p < .05$.

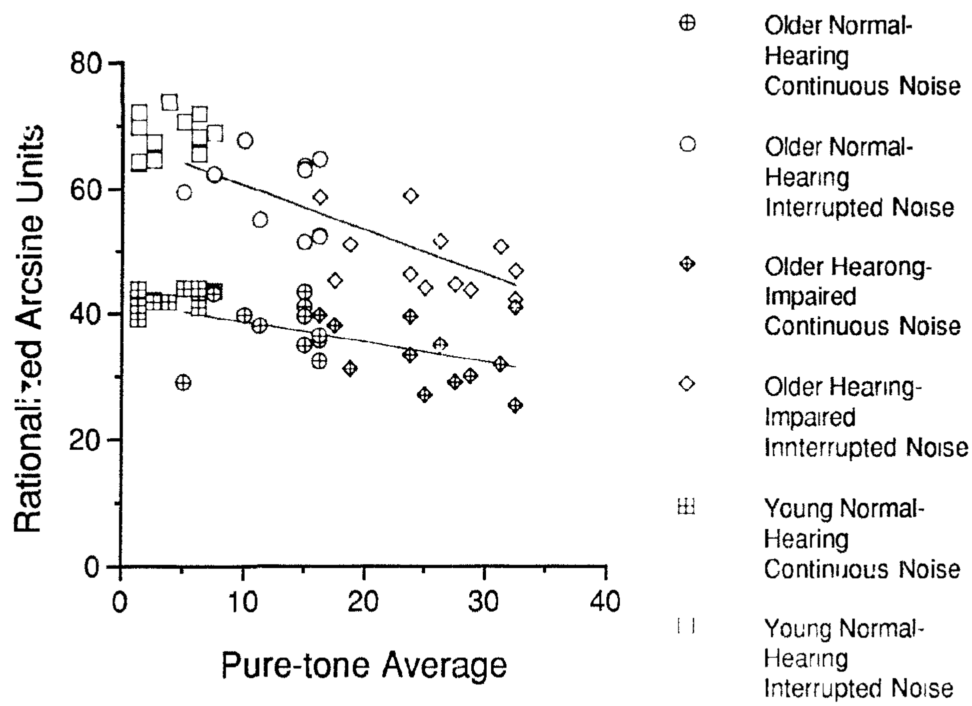

Figure 16: Bivariate scatter plots and respective linear regression lines for word recognition performance (in RAUs) as a function of PTA in continuous and interrupted noise for the ONH and OHI groups.

recognition performance deteriorates in both noises for the older hearing participants. The results of these analyses are presented in Tables 17 and 18. Violations of assumptions of linearity, normality, and homogeneity of variance were not revealed following examinations of scatterplots of residuals against predicted values, residuals against individual independent values, and individual independent values against predicted values. The slopes or regression coefficients (*B*) were also examined (i.e., to assess whether the population slopes or regression coefficients are different from zero). The analyses from separate *t*-tests are found in Table 19. For both noise conditions, the null hypothesis was rejected. That is, the separate slopes were different from zero, and therefore knowledge of PTA enhances the prediction of word recognition score. The bivariate scatterplots and respective linear regression lines for word recognition performance (in RAUs) and PTA as a function of noise condition are presented in Figure 16.

Several observations can be made while examining Figure 16. First, performance is negatively correlated to absolute hearing sensitivity, as indexed by the four-frequency PTA, among the older participants for both noise conditions. Second, the OHI data cluster to the right of the scatterplot, reflecting poorer absolute hearing sensitivity. Recall Figure 12 and Table 6 where pure-tone threshold data was presented and analyzed. Next, word recognition scores are higher in the interrupted broadband noise than in the continuous broadband noise, reflecting the release from masking in the former noise condition for all listeners. This is consistent with the data presentation in Figures 13 and 14. Further, within each noise condition, the ONH data tends to cluster higher on the ordinate reflecting the fact that in both noise conditions their word recognition performance was superior to the OHI group (see Tables 10 and 12). Finally, notice that the trend the data take, for both noise conditions, is one of a continuous distribution moving along the abscissa from data points of the normal-hearing to the hearing-impa .ed listeners.

Discussion

In general, the overall performance of the older listeners in quiet and noise in this experiment are similar to that of young listeners in the two previous experiments. That is, performance is superior in quiet, improves with increasing S/N, and is greater in the interrupted broadband noise than in the continuous broadband noise. There were, however, significant group differences in all three listening conditions in spite of participants being presented speech stimuli at the same SL.

In quiet, both the YNH and ONH groups had significantly higher word recognition scores than the OHI group. The difference is attributed to the greater loss in hearing sensitivity and subsequent reduced channel capacity above 2000 Hz in the hearing impaired group. The effect size was not large. It may have been the case that this difference would have disappeared had the speech stimuli been presented at a higher SL for the hearing impaired group. It has been found that maximum performance for presbycusic listeners may not be attained until SL presentation is greater than 40 dB (Gang, 1976; Gordon-Salant, 1987; Kasden, 1970; Linden, 1954).

In the continuous noise, there was an expected significant effect of S/N. All three groups performed differently with superior performance displayed by the YNH group followed by the ONH and OHI groups. The fact that the OHI group's performance was inferior to the normal-hearing groups is not surprising. As outlined in the introduction, there is a plethora of literature documenting inferior listening performance of the hearing impaired in competing background noise. The contribution of reduced high-frequency audibility and poorer frequency resolution are responsible (e.g., Bonding, 1979; Glasberg & Moore, 1986; Glasberg et al., 1984; Lutman, 1991; Lutman et al., 1991, Patterson et al., 1982; Nelson, 1991; Tyler et al., 1982). There may be concomitant central auditory effects that contribute to the differences between the OHI and YNH groups, as well; however, these data alone cannot give confirm that speculation.

The difference between the two normal-hearing groups is of interest. Although performance between the young and older groups was statistically equivalent in quiet, it was not the case in the competing continuous broadband noise. These results are similar to those of others who have reported impoverished speech recognition performance between young and older normal-hearing listeners only in conditions of competing stimuli (Dubno et al. 1984; Gelfand et al., 1986). Three plausible explanations can be offered for the performance disadvantage experienced by the ONH group in continuous noise First, although the ONH and the YNH groups had hearing thresholds within normal limits, there were some high-frequency sensitivity differences above 4000 Hz (see Figures 8, 9, and 11). It might be argued that this loss of audibility may have contributed to the decrease in performance. This seems unlikely, however, considering the fact that there is little acoustic information above 4000 Hz that contributes to recognition of consonant-vowel-consonant monosyllabic words (Egan & Wiener, 1946; French & Steinberg, 1947; Pollack, 1948). Recall also, that there were no differences in performance in quiet Further, the group mean pure-tone threshold was only mildly impaired. Seven participants had normal pure-tone thresholds of ≤ 25 dB HL at 8000 Hz.

A second offering, for the performance disadvantage experienced by the ONH group in continuous noise, may be inherent suprathreshold distortion within the older auditory system. Decreases in performance in spite of a reasonably high presentation levels is consistent with Plomp and colleagues' model of auditory handicap where one aspect of hearing impairment is characterized by suprathreshold distortion (e.g., Dreschler & Plomp, 1980, 1985; Festen & Plomp, 1981; Plomp, 1978, 1986; Plomp & Duquesnoy, 1982; Plomp & Mimpen, 1979; van Rooij & Plomp, 1989, 1990, 1992). The effect is analogous to listening at a reduced S/N in spite of apparently normal hearing sensitivity. In other words, the older listeners may be processing acoustic stimuli in the same manner as the younger listener, but they are operating at an effectively reduced S/N. This seems conceivable considering the fact that the both young and old normal-hearing groups performed the task at equivalent SLs. The source of the distortion may be either peripheral or central. One source that may allow the introduction of peripheral distortion is auditory filters widening with increasing age (Glasberg et al., 1984; Lutman, Gatehouse, & Worthington, 1991; Patterson et al., 1982). The reported effect sizes are, however, small and these studies have been attacked for the fact that hearing loss among participants may have been confounded with the effects of age. Other studies have offered that auditory filter shape/frequency resolution does not necessarily differ with age in normal-hearing older listeners or hearing-impaired older listeners when the effects of hearing loss are controlled (Peters & Hall, 1994; Peters & Moore, 1992a, 1992b). It appears then, that auditory filter shape, in older listeners with normal absolute thresholds, may not be abnormal. That being the case, it seems unlikely that the lower performance exhibited by the ONH group is a result of poorer frequency resolution. One has to admit that a normal audiogram and excellent word recognition in quiet does not preclude some other suprathreshold cochlear processing disruption that may influence listening performance in noise. A central auditory deficit(s) may furnish some suprathreshold processing distortion and hence foster the degraded performance among the older listeners. Central auditory processing dysfunction has been reported elsewhere in cognitively-intact elderly adults without a concomitant decline in hearing sensitivity or linguistic proficiency (Rodriguez et al., 1990). Attempting to identify the nature of that deficit on these data alone would be conjecture. One suggestion comes from Peters and Moore (1992b) who offer that the efficiency of the central detection process following peripheral auditory filtering decreases with aging. Efficiency of detection is represented by *K*. Values of *K*, indicating the S/N at the output of the auditory filter where a signal is at threshold, increase with aging. In other words, older listeners require a higher S/N from the auditory filter output for signal detection One may imply, for suprathreshold processing, older listeners require a higher S/N from peripheral output channels in order to achieve the same performance level as younger listeners As stated above, it reflects the fact that older listeners are functioning at a reduced S/N

Nonauditory central effects or linguistic incompetence may be offered as a inal suggestion for the cause of the performance differences observed between the young and older participants in the continuous noise condition The appeal of this suggestion is weak due to the fact that screening procedures were employed (i e., Mini-Mental State [Folsten, et al., 1975] and the Peabody Picture Vocabulary Test-Revised [Dunn & Dunn, 1981]) Admittedly, the these procedures do not claim sensitivity to all cognitive and linguistic parameters that may influence performance, but the word recognition task is not particularly cognitively or linguistically demanding It is also unlikely that response criteria differences that may be evident among older listeners would contribute to the performance difference on this speech recognition task (Jerger, Johnson, & Jerger, 1988; Sapp & McCarthy, 1993)

In the interrupted broadband noise listening condition there was again an expected main effect of S/N A positive correlation was found between S/N and word recognition scores. As well, significant linear regression equations were found for all groups. That is, knowledge of S/N enhances the prediction of word recognition scores for all groups. These findings were not unanticipated.

Group effects in the interrupted noise paralleled those in the continuous noise. That is, superior performance was displayed by the YNH group followed by the ONH and OHI groups, respectively. This finding would imply differing degrees of temporal resolution among the three groups of listeners. It was predicted that the OHI group would display poorer performance than the two normal-hearing groups as a consequence of their restricted listening bandwidth. That is, performance is attributable to hearing-impaired listeners' restricted low-frequency channel capacities which have inherently inferior temporal resolving abilities. Although the presbycusic listeners did receive some release from masking in the interrupted noise relative to the continuous noise, it was not as large as that experienced by the normal-hearing listeners. These results are consistent with others who report the release from masking is less favorable among presbycusic listeners and listeners with other sensorineural hearing pathology in competing interrupted broadband noise (de Laat & Plomp, 1983; Punch, 1978; Wilson & Carhart, 1969) and other time-varying maskers such as interrupted speech babble (Bergman, 1980), amplitude modulated noise (Bacon, Opie, & Montoya, 1994; Eisenberg et al., Festen, 1987; Shapiro et al., 1972; Souza & Turner, 1994; Takahashi & Bacon, 1992), and interfering speech (Festen, 1993; Festen & Plomp, 1990).

One is again faced with the task of attempting to account for the performance differences between the two normal-hearing groups in the interrupted broadband noise. As with the performance in the continuous noise, one could offer either differences in high-frequency bandwidth sensitivity or inherent suprathreshold peripheral or central distortion within the older auditory system. A contribution of other nonauditory central effects, linguistic incompetence, or response criteria differences may be unlikely as described above. It may be the case that the restricted peripheral auditory bandwidth of the older listeners, albeit mildly different than the young normal listeners, contributes to poorer temporal resolution. It seems unlikely that this is the case, as stated above. There is little acoustic information above 4000 Hz that would enhance performance on this word recognition task. The ONH participants had sufficiently wide enough auditory bandwidth to utilize high-frequency auditory filters with satisfactory temporal resolving capacities. One could also offer that the older ear's central temporal integrator/temporal window is broader and this alone could impair temporal resolution. Recall that the broader the temporal window, the longer the temporal integration or poorer the resolution. This is highly speculative and there is no reason to believe that this is the case. There is no available research to resolve this matter. One may again entertain the hypothesis that some other central auditory dysfunction may be a significant contributor.

The significant group differences found with the ANOVAs coupled with the significant correlation and linear regression analyses, found examining word recognition scores from the ONH and OHI groups collapsed across S/N for both continuous and interrupted broadband noise as a function of four-frequency PTA, are of interest. From observing the distribution of the data in Figure 16 and the significant linear relationship between absolute hearing sensitivity and word recognition performance, one may suggest that the dichotomization of normal-hearing versus hearing-impaired, albeit convenient and sensible, is likely oversimplified. The regression analyses suggest first, that the absolute sensitivity is continuously distributed, and second, not surprisingly, that PTA is linearly related to word recognition performance in noise. The YNH

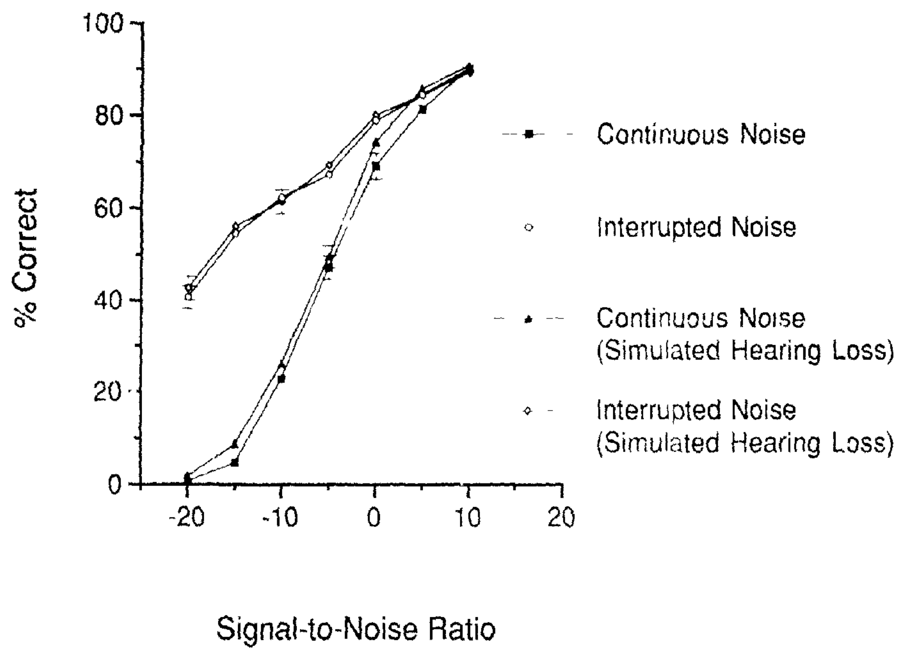

Figure 17: Figure 16 replotted with the YNH data superimposed on the ONH and OHI data. The ONH and OHI data are exact reproductions of the earlier figure and the YNH data was not incorporated into the regression analyses.

data was superimposed on the ONH and OHI data from Figure 16 and replotted in Figure 17. The ONH and OHI data are exact reproductions of the earlier figure and the YNH data was not incorporated into the regression analyses. Although age between the young and two older groups is not continuously distributed due to sampling techniques, it is interesting to look at the pattern that has emerged. The YNH data cluster to the upper right of each scatterplot reflecting, obviously, their superior performance and younger age. The YNH data appear to add a further piece to the puzzle That is, their word recognition performance suggests that the dichotomization of young versus older listener albeit convenient and sensible also, is likely oversimplified and possibly misleading. What emerges is a view that there is likely a progressive deterioration of threshold and suprathreshold processing with age. Gelfand and Silman (1985) agree with this sentiment that aging be viewed as a progressive process and not a static dichotomy of young versus old "There is a progression in reduced auditory functioning that may be steady or precipitous as a function of age, depending on the parameter under study" (p. 208) Findings of consonant recognition errors among listeners with normal hearing as a function of aging support this notion (Gelfand, Piper, & Silman, 1985, Gelfand et al., 1986) That is, older normal hearing listeners make similar consonant confusion errors in quiet and noise as do younger listeners This implies that the differences in performance with aging are quantitative rather than qualitative This may be the case with the observed differences between the YNH and ONH groups in absolute hearing sensitivity and suprathreshold performance reflected in pure-tone audiograms and word recognition in competing noise, respectively The performance of the OHI group may be viewed as a point further away on that continuum from the two normal hearing groups as their performance is exacerbated by poorer absolute hearing sensitivity.

Finally, the interaction of Group by S/N in the interrupted broadband noise is of interest. Post hoc regression analyses revealed a significant linear relationship between S/N and word recognition scores. Knowledge of S/N enhances the prediction of word recognition score for all groups Pair-wise comparisons of group regression slopes revealed that all comparisons were significantly different. In other words, all groups were differentially affected by the competing interrupted noise. As S/N deteriorates the differences between groups is magnified (see Figure 14). This is of note in light of the above discussion of the possibility of suprathreshold processing distortion within the auditory system of the older listener.

It stands to reason that some perceptual tasks will be more sensitive in detecting auditory dysfunction than others. It has been suggested that where differences have not been found between young and older listeners, it may be a result of performance indices not being sufficiently sensitive (Eisenberg et al., 1995; Gordon-Salant, 1987; Humes & Roberts, 1990; Souza & Turner, 1994; Takahashi & Bacon, 1992). Adding a time-varying competing stimulus may yield a more sensitive index for contrasting word recognition performance between young and old and between normal-hearing and hearing-impaired listeners (Eisenberg et al.; Takahashi & Bacon). It may be that the differences between young and older listeners, in speech understanding against a competing continuous noise, are a function of the inherent suprathreshold peripheral and/or central distortion within the older auditory system. Evaluating speech understanding in interrupted noise appears to be more sensitive in revealing differences in auditory function between listeners. That is, it provides a venue in which auditory processes can be engaged, and if compromised, be revealed to be compromised. It seems that the paradigm reveals the patency of the temporal processes that are responsible for the perceptual advantage (i.e., a release from masking) a listener has in interrupted competing stimulus.

Chapter 4

Addressing the Problem of Older "Normal-Hearing" Listeners: Reevaluating Word Recognition Performance in Continuous and Interrupted Broadband Noise by Normal-Hearing Listeners with a Simulated High-Frequency Hearing Loss

In the previous experiment it was speculated that the detriment in performance in the continuous and interrupted broadband noise exhibited by the ONH group, relative to the YNH group, could be a consequence of differences in high-frequency hearing sensitivity above 4000 Hz. This experiment sought to explore that speculation by retesting the YNH group with a simulated hearing loss similar to that of the ONH group. The purpose of this experiment was, therefore to investigate normal-hearing participants' performance in continuous and interrupted broadband noise as a function of S/N with and without a simulated high-frequency hearing loss above 4000 Hz.

Method

Participants

The 12 young adult university undergraduate and graduate students described as Group 1 in the two previous experiments served as participants.

Stimuli

The test stimuli consisted of the same recordings of the NU 6 lists one to four described in the previous experiments.

Apparatus

The equipment array was identical to that described in the previous experiment with the exception that the test stimuli were lowpass filtered to simulate a high-frequency hearing loss as in the first experiment. That is, the recorded stimuli were routed in series from the stereo cassette deck (JVC Model

DD-V7), passive analog filter (Krohn-Hite, Model 3340), clinical audiometer (Grason Stadler GSI 10 Model 1710-9700), and presented to each participant through the insert earphone (Etymotic Research Model ER-3A). The signal was lowpass filtered, at 4000 Hz with a rolloff slope of 48 dB/octave, to simulate a high-frequency hearing loss. This choice of filter cutoff and rolloff slope were employed in an effort to mimic the worst high-frequency audiometric configuration found in the ONH group in the previous experiment. That participant had a pure-tone threshold of 50 dB HL at 8000 Hz

Procedure

Testing was undertaken in one session of approximately one hour in duration one to two months following the previous test session. Participants were presented with the identical NU-6 stimuli at 30 dB SL re: their respective SRTs. The speech stimuli were again presented in quiet and in both noise conditions with S/Ns of 10, 5, 0, -5, -10, -15, and -20. The presentation order of lists, noise condition, and S/N was determined with a Latin square design. All test stimuli and noise competitors were presented monaurally to the right ear of each participant.

Results

Participants' responses were scored as total whole word percent correct. Mean word recognition performance in quiet was 94.3 % (*SE* = 0.73). Mean scores as a function of noise type and S/N are shown in Figure 18. Participants' word recognition scores in the unfiltered condition from the previous experiment are included as well. Participants again displayed the typical sigmoid performance-intensity functions in the continuous noise condition and a shallower performance-intensity function and improved overall performance in the interrupted noise condition.

Prior to subjecting the participants' proportional scores to inferential

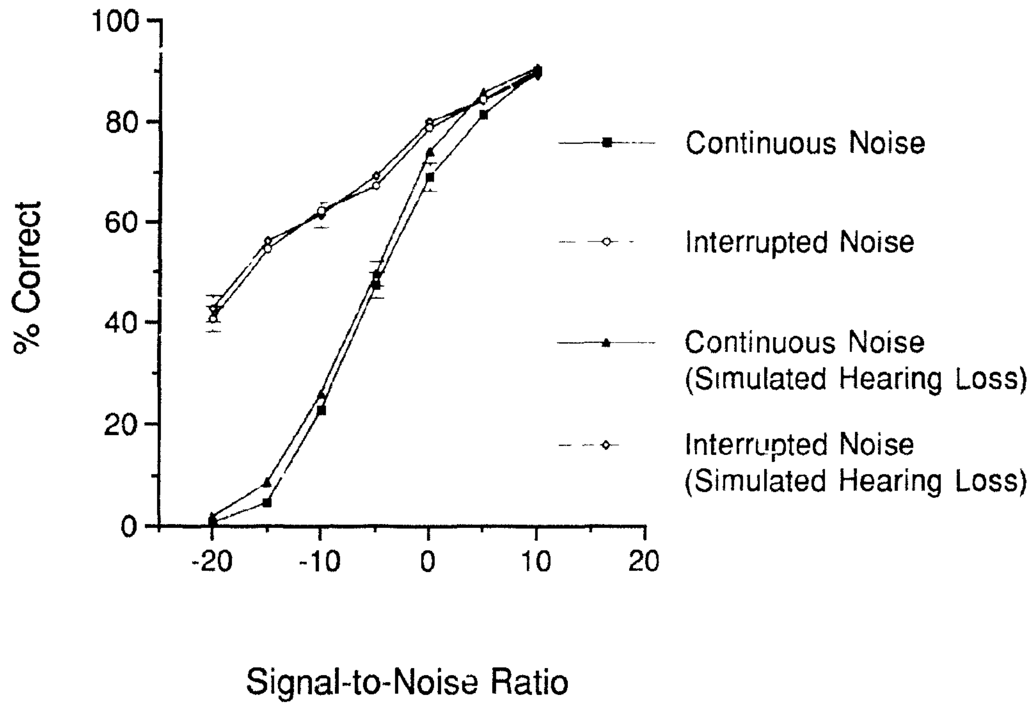

Figure 18: Mean percent correct word recognition score in continuous and interrupted broadband noise as function of Auditory Condition (i.e., unfiltered and simulated hearing loss via lowpass filtering at 4000 Hz) and S/N (*n* =12). Error bars represent plus/minus one standard error of the mean.

Table 20

Summary table for the two-factor within-subjects ANOVA investigating word recognition performance in continuous broadband noise as a function of Auditory Condition (i.e., unfiltered vs. filtered) and S/N.

Source	Sum of Squares	*df*	Mean Square	*F*	*p*	$\hat{\omega}^2$
Auditory Condition	643.90	1	643.90	18.61	.0012[a]	.42
Error	380.62	11	34.11			
S/N	241463.53	6	40243.92	563.88	.0001*[b]	.98
Error	4710.41	66	71.37			
Auditory Condition X S/N	188.15	6	31.36	.76	.604[c]	.00
Error	2722.51	66	41.25			

Note. *p* values following a Geisser-Greenhouse and Huynh-Feldt correction are [a].0012, .0012; [b].0001, .0001; and [c].544, .594 respectively.

* considered significant at $p < .05$.

Table 21

Summary table for the two-factor within-subjects ANOVA investigating word recognition performance in interrupted broadband noise as a function of Auditory Condition (i.e., unfiltered vs. filtered) and S/N.

Source	Sum of Squares	*df*	Mean Square	*F*	*p*	$\hat{\omega}^2$
Auditory Condition	13.43	1	13.43	.82	.385[a]	.00
Error	180.83	11	16.44			
S/N	44285.26	6	7380.88	126.81	.0001*[b]	.90
Error	3841.32	66	58.20			
Auditory Condition X S/N	66.50	6	11.08	.48	.821[c]	.00
Error	1522.70	66	23.07			

Note. *p* values following a Geisser-Greenhouse and Huynh-Feldt correction are [a].385, .385; [b].0001, .0001; and [c].742, .821 respectively.

* considered significant at $p < .05$.

statistical analyses they were transformed to RAUs (Studebaker, 1985) With respect to mean word recognition performance in quiet, no statistically significant difference was found between the YNH group's performance, $t(11) = -1.57$, $p = .145$. In other words, there was no effect of filtering on word recognition performance in quiet.

To investigate mean word recognition performance differences as a function of filtered and unfiltered listening and S/N for both continuous and interrupted broadband noise conditions, separate two-factor within-subjects analyses of variances (ANOVAs) were undertaken The results of each separate ANOVA are presented in Tables 20 and 21 Not surprisingly, a significant main effect was observed for S/N with both continuous broadband and interrupted noise conditions ($p < .05$) Again, performance increased with increases in S/N regardless of noise condition. A significant main effect for filtering (i.e., simulated hearing loss) was only observed in the continuous noise condition ($p < .05$). Surprisingly, superior performance was exhibited for the filtered listening condition (i.e., the simulated hearing loss condition) in the continuous noise condition. No interactions of main effects were significant in either noise condition ($p > .05$).

Discussion

The findings of this experiment with the simulated high-frequency hearing loss are, in general, consistent with the previous findings. Performance was superior in quiet, improved with increases in S N regardless of noise condition, and a release of masking was observed in the interrupted noise relative to the continuous noise.

It was anticipated that there would be no significant differences between the filtered and unfiltered listening conditions This hypothesis was based on the observation that there is little acoustic information above 4000 Hz that contributes to recognition of consonant-vowel-consonant monosyllabic words (Egan & Wiener, 1946, French & Steinberg, 1947; Pollack, 1948). In that light the absence of Group effects in quiet and interrupted noise are no surprise. A significant Group effect was observed only in the continuous broadband noise condition. It was somewhat unexpected that the filtered listening condition was superior to the unfiltered listening. This circumstance may be a consequence of practice. It should be noted that the participants, over the course of two experiments, listened to each of the four NU-6 lists seven or eight times under various background conditions. Considering this, it is not surprising that they would gain some familiarity with the speech stimuli. A practice effect has been reported while testing speech recognition in noise (Jerger, Malmquist, & Speaks, 1966; Shore, Bilger, & Hirsh, 1960).

The finding that performance in both noise conditions was not inferior in the simulated hearing loss above 4000 Hz sheds some light on the interpretation of the previous experimental results Although not conclusive, it does diminish the suggestion that the differences in high-frequency hearing sensitivity between the ONH and YNH group contributes to performance differences in word recognition in continuous and interrupted noise.

General Discussion

Summary of Experimental Findings

In the first experiment of this dissertation, it was hypothesized that on tasks challenging the temporal resolving capacity of the auditory system, a listener's performance should be governed by the functional ability of their cochlear output channels. The more channels available, and particularly the more high-frequency channels where temporal resolving capabilities are better, the better performance should be. It was hypothesized that if hearing-impaired subjects' detriment in performance on tasks, revealing auditory temporal processing, was a repercussion of restricted low-frequency channel capacity, normal-hearing subjects should exhibit a similar disadvantage in performance on the same task if studied under conditions that simulate a high-frequency hearing loss. Employing the D.P. Phillips et al (1994) interrupted noise paradigm, it was found that the normal-hearing participants with a simulated high-frequency hearing loss displayed poorer performance in the interrupted broadband noise but not in the continuous broadband noise, relative to their normal listening performance. The spectra of the two noises were essentially the same and they differed only in their temporal properties As such, performance differences had to be tied to the temporal dissimilarities of the two noises. It was concluded that the performance deficit the normal-hearing participants displayed in the interrupted noise was a consequence of restricted auditory bandwidth. That is, their less-than-favorable performance in the interrupted noise was attributed to their selective use of low-frequency cochlear channels, which are normal, but have inherently poorer temporal resolution abilities. The inability to resolve speech information between noise bursts is a form of temporal processing deficit.

The effect of presentation level on word recognition performance-intensity functions in both continuous and interrupted broadband noise was explored in the second experiment. Normal-hearing participants were tested at 30 and 50 dB SL. It was discovered that there was an effect of presentation level on word recognition performance in the interrupted noise only. These findings revealed differing processes underlying listening in both noises. In continuous noise, performance is contingent on spectral audibility. In other words, the recognition of speech stimuli is govern by audibility of that speech stimulus. For any masker/maskee combination, once a masker has caused a threshold shift, further increases in the masker level result in a linear equal dB shift in the maskee threshold. Intelligibility of speech in noise is linear for SLs of noise from 20 to 90 dB (Hawkins & Stevens, 1950). Because this linear relationship exists, and since relative levels of masker and speech were maintained when shifting SL (i.e., the S/Ns were the same in both SL presentations), performance-intensity function shapes were preserved. The relationship of the speech stimuli and competing noise remained the same at the two suprathreshold levels and consequently the audibility of the speech stimuli remained the same as well (i.e., the performance-intensity function remained the same). In the interrupted noise, it was concluded that listening was influenced by forward and backward masking. The silent intervals between bursts of noise are subject to spill-over from the noise as a consequence of forward and backward masking. The time for recovery from forward and backward masking is independent on the masker level, and as a result, the slopes of backward and forward masking become steeper at increasing masker levels. It stood to reason that superior performance in interrupted noise at the higher 50 dB SL occurred because a of greater release from masking. That is, since the decay of masking was more gradual at 30 dB SL, the silent gaps between noise bursts were less effective than at 50 dB SL With higher masker levels the masking decayed faster, increasing both the depth and width of the silent gaps

In the third experiment of the dissertation, performance-intensity functions for word recognition, in continuous and interrupted broadband noise as a function of S/N, were examined among young normal-hearing adults, cognitively-intact older normal-hearing adults, and cognitively intact age matched presbycusic adults Group differences in performance were found in all experimental conditions of quiet, continuous and interrupted broadband noise. Both normal-hearing groups displayed superior performance in quiet to the presbycusic participants It was induced that the difference was due to the reduced hearing sensitivity above 2000 Hz in the hearing impaired group It was noted that the presentation level for the speech stimuli was at 30 dB SL and maximum performance for presbycusic listeners is not often attained until SL presentation is greater than 40 dB In both noises word recognition scores increased with improving S/Ns and were more favorable in the interrupted broadband noise for all groups of participants The YNH group's performance was superior followed by the ONH and OHI group's performance for both noise conditions The OHI group's lower performance was not surprising Reduced high-frequency audibility and poorer frequency resolution along with restricted low-frequency channel capacity were identified as being responsible for performance detriments in the continuous and interrupted broadband noise respectively It was speculated that the differences in performance between the YNH and ONH participants could be a consequence of either reduced auditory bandwidth above 4000 Hz available to the older participants inherent peripheral or central distortion in the older auditory system, and/or nonauditory central effects or linguistic incompetence There was diminished appeal for the first and last explanation: Little acoustic information above 4000 Hz contributes to recognition of consonant-vowel-consonant monosyllabic words. Cognitive and linguistic screening procedures were employed and the word recognition task is not particularly cognitively or linguistically demanding. The significant linear relationship between absolute hearing sensitivity and word recognition performance among the older listeners suggested that the dichotomization of normal-hearing versus hearing-impaired may be an oversimplification. The trend of the data in Figure 17 also suggested that the dichotomization of young versus old may also be oversimplified and possibly misleading. It may be more appropriate to view changin auditory function with aging as a gradual process and not a static dichotomy of young versus old or norm... aring versus hearing-impaired. That is, with aging one sees a progressive deterioration of absolute sensitivity and suprathreshold processing. The observed suprathreshold performance differences between the three groups may then be perceived as points on a continuum where the OHI group's performance is further from the two normal-hearing groups, exacerbated by poorer absolute hearing sensitivity.

Normal-hearing participants' performance in continuous and interrupted broadband noise as a function of S/N with and without a simulated high-frequency hearing loss above 4000 Hz was examined in the final experiment of the dissertation. This experiment was undertaken in an effort to shed light on the contribution of audibility above 4000 Hz to word recognition performance. Performance in quiet and interrupted broadband noise were equivalent with the simulated hearing loss and without. Performance in the continuous broadband noise condition was, surprisingly, slightly superior for the simulated hearing loss. This effect was attributed to practice. The finding that performance in both noise conditions was not inferior with the simulated hearing loss above 4000

Hz, although not conclusive, diminished the suggestion that the differences in high-frequency hearing sensitivity between the ONH and YNH group contributed to their performance differences in word recognition in continuous and interrupted noise.

Do Older Listeners Have a Temporal Resolution Deficit?

It was noted above that auditory temporal resolution refers to the ability of a listener to resolve or separate auditory events and/or detect changes in auditory stimuli over time. As well, auditory temporal phenomena are revealed differently depending on the psychophysical technique engaged. Research investigating performance of presbycusic listeners on tasks revealing temporal phenomena have been equivocal, as with other listeners suffering from sensorineural hearing impairment. It was suggested that differences among studies may be attributed to varying task demands that either exploit impaired (typically high-frequency) cochlear channel deficits or equate performance with tasks designed for normal functioning (typically low-frequency) cochlear channels. It has also been suggested that the more demanding the perceptual task, the more sensitive it will be in detecting auditory dysfunction. It was also speculated that where differences have not been found between young and older listeners, it may be a result of performance indices not being sufficiently demanding. In studies where differences in hearing sensitivity have been controlled, performance differences have been attributed to age-related changes in the auditory system (i.e., specifically central auditory changes).

It was outlined above that the interrupted noise paradigm could reveal auditory temporal phenomena. Adequate temporal resolution is required as the listener must sustain the temporal gaps in the masker thereby taking advantage of the favorable S/Ns. The release from masking in interrupted noise must be limited by the auditory system's ability to resolve acoustic information in the silent gaps between the successive noise bursts. The interrupted noise paradigm can reveal, not only expected deficits in temporal processing associated with the peripheral hearing loss in presbycusic listeners but also, any deficit that may be a consequence of central auditory factors independent of the peripheral pathology.

As to the question "Do older listeners have a temporal resolution deficit?", the answer with the interrupted noise paradigm has to be a definitive yes. Older normal-hearing listeners and participants suffering from presbycusis exhibited poorer performance in the interrupted noise compared to young normal-hearing listeners. Intuitively, one must conclude that if the task makes demands on the temporal resolving capability of the auditory system, then the auditory system of older listeners must have impoverished temporal resolution. Although the task is somewhat artificial and does not exactly mimic everyday listening conditions, it is similar in that listeners are often presented with the task of attempting to understand speech in background noise that fluctuates and is intermittent. The perceptual difficulty displayed by the older listeners in the interrupted noise task may be akin to the difficulties experienced in the real world.

Dealing with the question "Do older listeners have a temporal resolution deficit?" may be problematic because of the lack of consensus as to how to define temporal resolution or what temporal processing entails (Moore et al., 1989; Phillips, 1995). This has been particularly burdensome with hearing-impaired listeners. Central to this point is the need to appreciate differences between what information is provided by task performance, the perceptual difficulty(s) experienced by the listeners, and the underlying process involved in the impairment. "The description of a listener as having a disorder of temporal processing actually provides little information about what perceptual processes are impaired" (Philips, pp 342-343). Moore, on defining temporal resolution, states:

> If it is defined operationally, for example, as the threshold measured in a particular task such as gap detection, this leads to the conclusion that cochlear impairment does sometimes lead to reduced temporal resolution. If, on the other hand, it is defined in terms of the parameters of a model of the underlying processes (for example, the ERD [equivalent rectangular duration] of the temporal window), then we would conclude that there is little or no evidence that the cochlear impairment leads to deficits in temporal resolution. The first definition may be more helpful in understanding the difficulties experienced by the hearing impaired The second definition may be more helpful in understanding the underlying processes (Moore p 1274)

The bottom line is that if performance is impaired on a task that reveals temporal phenomena, one may conclude that the listener has impaired temporal resolution ability for that task. The task performance may say nothing about the underlying process governing that performance. One can only make inferences from the task performance to the perceptual difficulties experienced by the listener in everyday life.

Where is the Temporal Resolution Deficit in the Older Listener?

Recall that the model of temporal resolution, proposed by Moore (1989, 1993), envisioned stimuli passing in series through four stages from the periphery to the central nervous system: bandpass auditory filter, nonlinear square-law device, temporal integrator or temporal window, and a central decision device. As the first two stages of the model were conceptualized as occurring in cochlea while the latter two stages in the central auditory system, it was obvious that temporal resolution deficits could either be peripheral or central in nature.

The findings of the first experiment, where performance was examined among normal-hearing listeners with and without a simulated hearing loss, and those of D.P. Phillips et al. (1994) confirmed that restricted low-frequency auditory channel bandwidth listening can account for deficits in word recognition with competing interrupted noise. This confirms the notion that low-frequency auditory channels have inferior temporal resolving abilities at least in the word recognition in continuous/interrupted noise paradigm employed here The findings do not, admittedly, address directly what factor(s) may be responsible for impoverished performance among some listeners. It may be the case that inherently longer response times of peripheral low-frequency channel filters, as a consequence of longer ringing after the offset of stimulus input relative to high-frequency channel filters, are responsible for poorer temporal resolution. On the other hand, it may be the case that peripheral manipulation (e g., lowpass filtering as employed in Experiment 1) or peripheral high-frequency hearing loss (e.g., as investigated by D.P. Phillips, 1994) reveals an inherently inferior, although normal, central mechanism. For example, the shape of the ear's temporal window/integrator increases slightly with decreasing center frequency (Plack & Moore, 1990). Temporal resolution may be inferior due to longer central integration as a consequence of broader temporal windows. Finally, it may be the case that an interaction of both peripheral and central factors are responsible for impaired performance. Depressed word recognition performance accompanying reduced high-frequency bandwidth must then, inevitably, be viewed as a consequence of either a factor(s) in the peripheral (e.g., ringing in the auditory filters) or central (e.g , broader temporal windows) auditory system and/or an interaction of peripheral and central factors.

The results of Middelweerd et al (1990) and Rappaport et al (1994) suggested that word recognition performance evaluated against a time-varying competing stimulus (i.e., amplitude-modulated or interrupted) may reveal central auditory dysfunction among listeners with normal peripheral auditory function. Unfortunately, the findings of the third study cannot definitively ascribe the performance detriments, observed in the older listeners, to either peripheral or central dysfunction alone. Obviously the poorest performance by the OHI group has a peripheral component, namely their reduced auditory bandwidth The central anatomical, histological, physiological, and morphological changes observed in both the human and animals invite the possibility of a central component to the older listener's poorer performance It is acknowledged that these central auditory system changes may be evoked by long standing peripheral hearing loss. Again, although structural changes are observed in the organism, their functional significance remains to be demonstrated

Willott (1991) suggests that separation of peripheral and central auditory dysfunction in the presbycusic listener may be impossible for two reasons First, impaired peripheral input to the central auditory system will likely disadvantage central processing. Second, the response properties of the central auditory system may become modified following prolonged exposure to distorted or attenuated input from an impaired periphery In this regard, studies in animals have shown that even in adults, focal peripheral lesions can lead to dramatic changes in the central "representation" of the cochlea (e.g., Harrison, Nagasawa, Smith, Stanton, & Mount, 1991; Rajan, Irvine, Wise, & Heil, 1993; Robertson & Irvine, 1989; Willott, Aitkin, & McFadden, 1993), even if one does not know what functions the rewired tissue can support Willott suggests that it may be fruitful to adopt an interactive approach That is,

> resolution of the question of the contributions of cognitive-linguistic, peripheral, and central processes to speech perception may be reached by implicating all three in an interactive mechanism. .The term "interactive" is preferred in the present context because of its generality. An interaction can be multiplicative, but it can also be occlusive, additive, or even subtractive It seems that such instances may often apply to presbycusis From the interactive perspective, the most important questions do not involve "which" age-related change is responsible for deficiencies in speech The questions center on the contribution of each and the manner in which they interact (Willott, pp 245-246)

Proposed Mechanisms for Impaired Performance in Interrupted Noise by Presbycusic Listeners

It was suggested earlier that two phenomena were responsible for the masking effect on speech intelligibility observed in interrupted noise with monosyllabic stimuli. The first was due to the simultaneous masking during the noise burst while the other was temporal masking during the inter-burst interval (Dirks et al., 1969, Dirks & Bower, 1970) It was suggested that the silent intervals were not immune from the influence of noise bounding them They were subject to spill-over from the noise as a consequence of forward and backward masking. In order for the listener to acquire a release from interrupted masking, relative to continuous masking, he/she has to sustain the temporal gaps in the masker thereby taking advantage of the favorable S/Ns. The release from masking in interrupted noise is therefore limited by the auditory system's ability to resolve acoustic information in the silent gaps between the successive noise bursts. Presbycusic listeners are able to achieve a release from masking; however, they are not as efficient as normal-hearing listeners. In other words, listeners with presbycusis have a temporal resolution deficit compared to normal-hearing listeners

What are the mechanisms underlying the deficit? During the noise bursts, presbycusic listeners are compromised at high frequencies by poor audibility and poorer frequency resolution as a consequence of broadened insensitive auditory filters in the impaired region of the cochlea The broad auditory filters make them more susceptible to interference from noise That is, a broadened filter passes more noise components and, thereby, reducing the effective S/N and making detection of the speech signal more difficult As well, the absence of normal sharp frequency tuning curves, accompanying broad auditory filters, underlies an inability to resolve spectral peaks and valleys in speech. This may be the case, as well, in the low frequency regions despite their normal or near normal auditory thresholds. Auditory filters have been found to be abnormal in hearing-impaired listeners where their auditory sensitivity is normal or near normal (Lutman et al., 1991; Pick & Evans, 1983; Wightman et al., 1977).

The effective glimpsing during the silent intervals between the noise bursts is governed by forward and backward masking effects The reduced release from masking experience by the hearing-impaired listeners in the high frequencies is a consequence of strong temporal masking at low sensation levels. The recovery from masking depends on the sensory response evoked by the masking stimulus (Nelson & Freyman, 1987). Due to their reduced hearing sensitivity, the masker is received at a much lower sensation level. That is, "large sensitivity losses reduce the sensory response to high SPL maskers so that the recovery process is slower, much like the recovery process for low-level stimuli in normal-hearing listeners" (Nelson & Freyman, p.709).

This is what was observed in the second experiment with the normal-hearing listeners at the lower SL presentation. The release from masking in the lower frequencies may be a consequence of reduced auditory filter width. Recall that bandwidths of auditory filters decrease with decreasing frequency. Further, auditory filters ring after the offset of input and the decay of the ringing is inversely proportional to the bandwidth of the filter. Presbycusic listeners' detriment in performance may be a consequence of restricted low-frequency channel capacity where temporal resolution is inherently inferior due to post stimulus presentation ringing in the auditory filters. An additional downside of low frequency channels is that temporal windows, as well, broaden (Plack & Moore, 1990). Recall that the broader the temporal window, the longer the temporal integration or poorer the resolution.

The contribution of comodulation masking release has been suggested to play a small role in the release from masking observed in time-varying maskers (Festen, 1993; Festen & Plomp, 1990). Comodulation masking release is an across-frequency mechanism which provide the means for the auditory system to integrate cues in the company of a signal from different frequency bands and to acquire a lower threshold than without masker comodulation (Hall, Haggard, & Fernandes, 1984). The effective release from masking was only 1.3 dB for speech reception threshold masked by an interfering voice (Festen). Comodulation masking release is not significantly different among young and older listeners where their hearing sensitivity is relatively normal (Peters & Hall, 1994).

The mechanisms contributing to the impaired performance of the presbycusic listener to this point have been accounted for by peripheral attributes. It was suggested above that there may be inherent suprathreshold distortion within the older auditory system. In terms of temporal resolution, they could take the form of changes in the temporal integrator or decision device. A broadened temporal window and/or reduced sensitivity of the decision device would impair the temporal resolving capacity of the listener. If these changes accompany aging they would exacerbate the peripheral dysfunction in the presbycusic listener. This is highly speculative and there is no available research to provide insight into this matter.

Comparing the Performance Between Normal-Hearing Listeners with Simulated Hearing Loss and Hearing-Impaired Listeners

It is worthy to note in Experiment 1 that although the normal-hearing participants with the simulated hearing loss in the interrupted noise condition matched the effect of the performance of the sensorineural impaired group of D.P. Phillips et al. (1994) study, the effect size was modestly reduced. This is consistent with other reports that note although performance of normal listeners, with simulated hearing losses, mimics cochlear hearing-impaired subjects on temporal resolution tasks, it is superior (Humes, 1990; Zwicker & Schorn, 1982). This is not entirely surprising considering that distortions may be imposed by the impaired cochlea (Plomp, 1978, 1986).

This raises the issue of comparing the performance between normal-hearing listeners with simulated hearing loss and hearing-impaired listeners. It is recognized that modeling hearing-impairment with low-pass filtering is imperfect as normal-hearing listeners' suprathreshold cochlear function (e.g., loudness recruitment) above the cutoff frequency is normal while to the contrary with cochlear impairment. Further, the simulated hearing loss via filtering in Experiment 1 and 4 did not match perfectly the actual loss of the D.P. Phillips et al. (1994) participants nor the OHI participants. Narrowband noise masking may have been used as an alternative to simulate hearing impairment as it can shift thresholds in specific frequency regions and simulate loudness recruitment in those regions. It is should be recognized, however, that low-pass filtering may be a better approximation of hearing-impairment than narrowband noise masking for several reasons. The first, is that it has been demonstrated that employing noise-masked normal listeners as a model of sensorineural hearing loss "cannot account for data from impaired listeners on various measures of temporal resolution"(Humes, Espinoza-Varas, & Watson, 1988, p. 200). Second, physiological data suggests that noise masking does not imitate peripheral auditory function in the impaired cochlea (Phillips, 1987; Phillips & Hall, 1986). Finally, in the only study comparing filtering and narrowband noise masking to simulate hearing loss, the latter has failed to provide a better simulation of hearing loss than the former (Fabry & Van Tasell, 1986). At any length, caution must be exercised when generalizing findings from normal-hearing listeners with simulated hearing-impairments to the cochlear impairment.

Future Research

As is usually the case with most research, when one project ends it spawns numerous others. Many questions have arisen through the course of this work. The first is whether the temporal resolution deficit, evident among the presbycusic participants here, would be found in other listeners with different cochlear (e.g., Meni`ere's disease) or retrocochlear pathology (e.g., eighth nerve or temporal lobe lesions)? A forth group of participants (i.e., young listeners with matched hearing-impairment to the presbycusic participants) was to be included in the third experiment of the dissertation. The restricted availability of these individuals precluded their inclusion. Testing hearing loss matched young and older listeners may provide insights into any differences in central auditory processing between the two. It would be of interest to evaluate other hearing-impaired listeners with different audiometric configurations (e.g., impaired low-frequency sensitivity with normal high-frequency thresholds and listeners with "flat" hearing losses). It also remains to be seem whether listeners who display impoverished temporal resolution with the paradigm, show similar detriments on other temporal resolution tasks. Finally, there is a need for more comprehensive evaluation of developmental effects on word recognition in competing stimuli. It was suggested that aging be viewed as a progressive as opposed to a static dichotomy of young versus old. A comprehensive development study from the first decade of life may reveal an initial improvement in performance followed by a progressive deterioration in advancing years.

FOOTNOTES

[1]The most common methods of inferring frequency selectivity is to measure the psychophysical tuning curve (e.g., Moore, 1978, Zwicker, 1974) or to calculate the auditory filter shape from thresholds of tonal signals in various noise maskers (e.g., Houtgast, 1977; Patterson, 1976). The psychophysical tuning curve resembles the inverted filter shape and shows marked asymmetry in the "tails" of the filter far from the center frequency. The derived filter shape is for the most part symmetrical at moderate intensities. The discrepancy in filter shapes arises in large part from the fact that psychophysical tuning curves are plotted on a logarithmic scale while derived filters are plotted on a linear scale (Glasberg et al., 1984).

[2]The power of each tract was determined using the formula: $P = 1/L * \Sigma_{t=0}^{L} s^2(t) * dt$ where P = signal power (W); L = length of track (s); s(t) = sample value @ time = t; and dt = sampling interval (50 µs).

[3]Cohen (1977) suggests the size of an effect be described as small, medium, or large based on the value of ω^2. Experiments that produce ω^2 of .01, .06, or .15 are deemed to have small, medium, and large effect sizes, respectively.

[4]In fixed effects factorial ANOVAs a distinction has been made between the standard omega squared and a partial omega squared (e g., Keppel, 1991, Keren & Lewis, 1979). The standard definition relates the variance estimate of factor *X* to a variance estimate of all sources variance in the design This procedure which is adopted for single-factor between subjects designs has been challenged with factorial designs. Keppel (1991; personal communication, April 21, 1995) advocates a definition that is continuous with the single factor between-subjects design regardless of the experimental

complexity. The differences in the definitions relates to the definition of the denominator summing the variance component for the effect and the error One may sum the estimated variance components for all sources in the analysis or just the variance component for the effect and the error associated with the effect only. The definition for partial omega squared chooses the latter (Keppel, 1991; Keren & Lewis). As such, "effects other than the one under consideration have been partialled out" (Keren & Lewis, p. 123).

[5]The effect is more pronounced with forward masking than backward masking. A number of researchers have questioned the nonlinear relationship between backward masker level and maskee level (e.g , Fastl, 1976; Moore, 1989) due to the poor reproducibility and large intersubject variability.

[6]Scores of 20 or less are "found essentially in patients with dementia, delirium, schizophrenia or affective disorder and not in normal elderly people ." (Folstein et al., p. 196).

APPENDIX

The purpose of this test is to determine how you perceive words in listening conditions of quiet and noise. Each word you will hear will have one syllable like "boat" or "home". Each time you hear a word just repeat it. Sometimes the words will be difficult to understand. It is okay to guess on these words. Do you have any questions?

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